GEM TPC – design and performance

Instrumentation Division Seminar

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Overview

- LEGS experiment.
- Why was the TPC necessary ?
- What were requirements and design solutions for the TPC ?
- Calibration procedures and coordinate determination.
- Track construction and systematic errors.
- Spatial and timing resolution.
- Particle identification, spatial and momentum reconstruction.
- Pion photo-production preliminary asymmetries.

The LEGS TPC Team

BNL LEGS:
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Graham Smith
Don Makowiecki
Tom Tsang
Kim Ackley
Kevin Wolniewicz
John Triolo
Ron Angona
Howard Hansen
Don Pinelli

The LEGS Facility

Beam

Highly Polarized (>90%) Compton Backscattered Photons
Linear and Circular Polarization, $E_\pi < E_\gamma < 470$ MeV: Covers Δ region

Target

Highly Polarized Frozen Spin HD Target
Longitudinal Polarization with $P_H \sim 60\%$, $P_D \sim 30\%$

Detector

TPC
Array of 432 NaI(Tl) blocks
Wall of 64 Plastic Scintillator Bars
Wall of 186 Pb-glass blocks

Double-polarization observables
on the nucleon
in the $\Delta(1232)$ P_{33} region

$$\vec{\gamma} p \rightarrow \pi^+ n \qquad \vec{\gamma} n \rightarrow \pi^- p$$

$$\vec{\gamma} p \rightarrow \pi^0 p \qquad \vec{\gamma} n \rightarrow \pi^0 n$$

We can see all 4 pion channels simultaneously.

Polarization Observables

P_γ^C γ beam circular polarization, +1 is right circular for spin along +z (downstream)

P_γ^L γ beam linear polarization, +1 or horizontal for electric field along x

P_X^V Target vector polarization, +1 for spin along +z (downstream)

P_X^T Target tensor polarization, for X=D only (zero for H)

$$\frac{d\sigma}{d\Omega}(\theta,\phi) = \frac{d\sigma_0}{d\Omega}(\theta)\times\left\{\begin{array}{lcr} & 1 & \\ +P_\gamma^L \cos 2\phi & \times & \Sigma(\theta) \\ +\frac{1}{\sqrt{2}} P_X^T \cos 2\phi & \times & T_{20}^L(\theta) \\ +P_\gamma^L P_X^V \sin 2\phi & \times & G(\theta) \\ -P_\gamma^C P_X^V & \times & E(\theta) \\ +\frac{1}{\sqrt{2}} P_X^T & \times & T_{20}^0(\theta) \end{array}\right\}\begin{array}{l} \\ \\ D\ only \\ \\ \\ D\ only \end{array}$$

Measured

Known & settable

To be determined by solving linear system

Spin Sum Rules at LEGS

- **Gerasimov-Drell-Hearn**

$$-\kappa^2 \frac{\alpha}{2m^2} = \frac{1}{4\pi^2} \int_{E_\pi}^{\infty} \frac{\sigma_{1/2} - \sigma_{3/2}}{E_\gamma} dE_\gamma$$

Anomalous
magnetic moment

65% energy coverage at LEGS

- **Forward Spin-Polarizability**

$$\gamma_0 = \frac{1}{4\pi^2} \int_{E_\pi}^{\infty} \frac{\sigma_{1/2} - \sigma_{3/2}}{E_\gamma^{\ 3}} dE_\gamma$$

Chiral
perturbation theory

90% energy coverage at LEGS

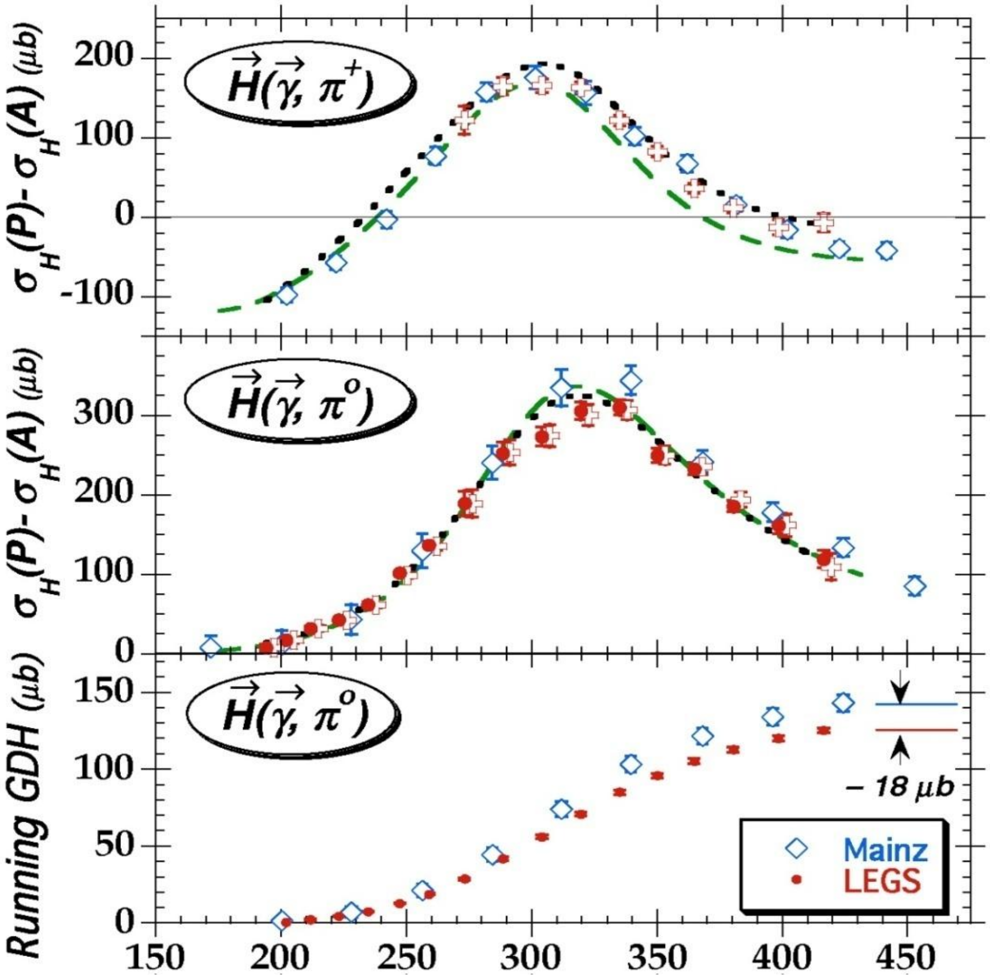
- **LEGS Energy Range**

$$E_\pi < E_\gamma < 470\,MeV$$

- **Our Focus** Neutron Sum Rules

Physics at LEGS is Dominated by the Δ Resonance

Proton Spin Difference Cross Sections



$$\hat{E} = \sigma_0 \quad E = \sigma_{1/2} - \sigma_{3/2}$$

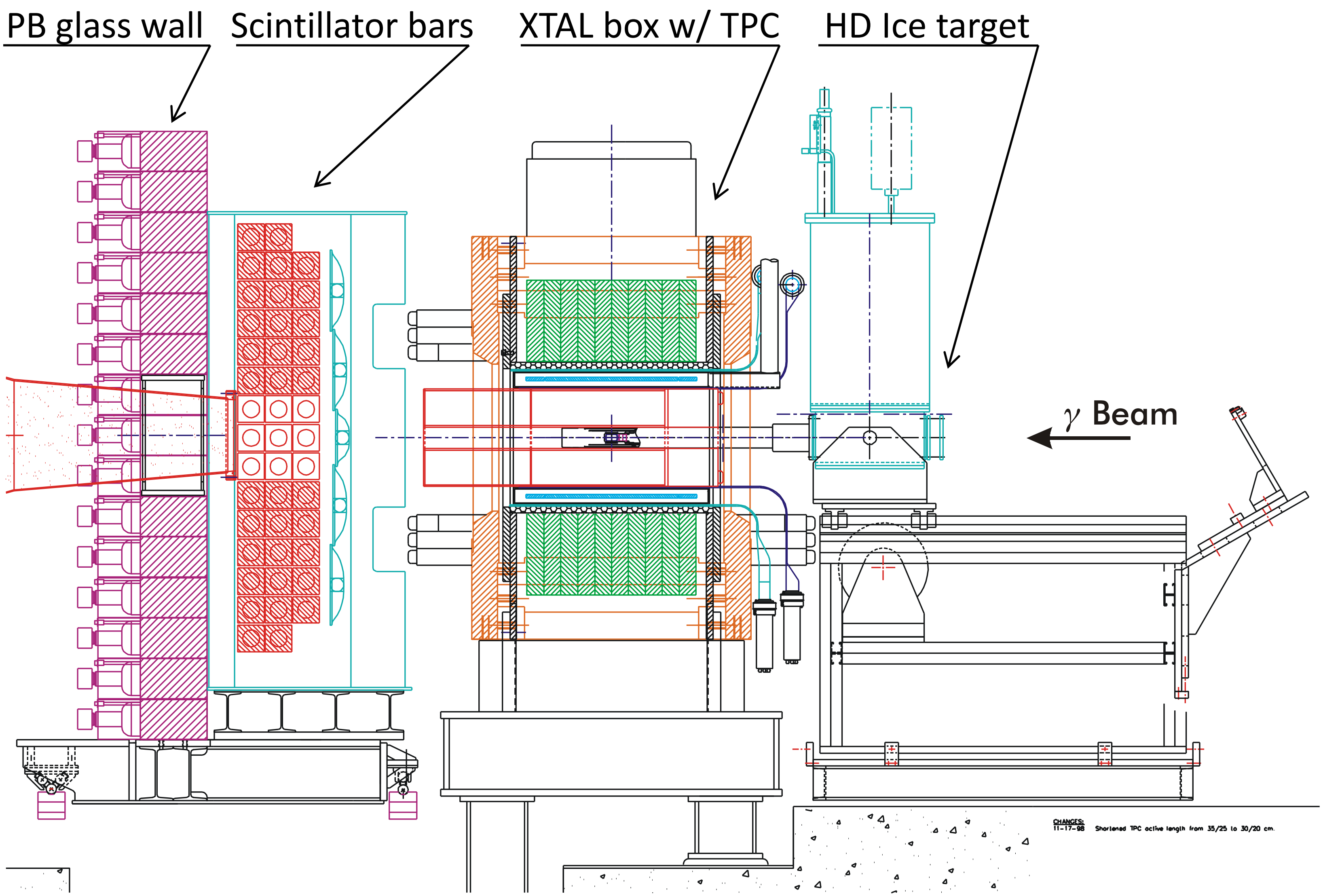
S. Hoblit, et al. PRL 102, 172002 (2009)

GDH integrand

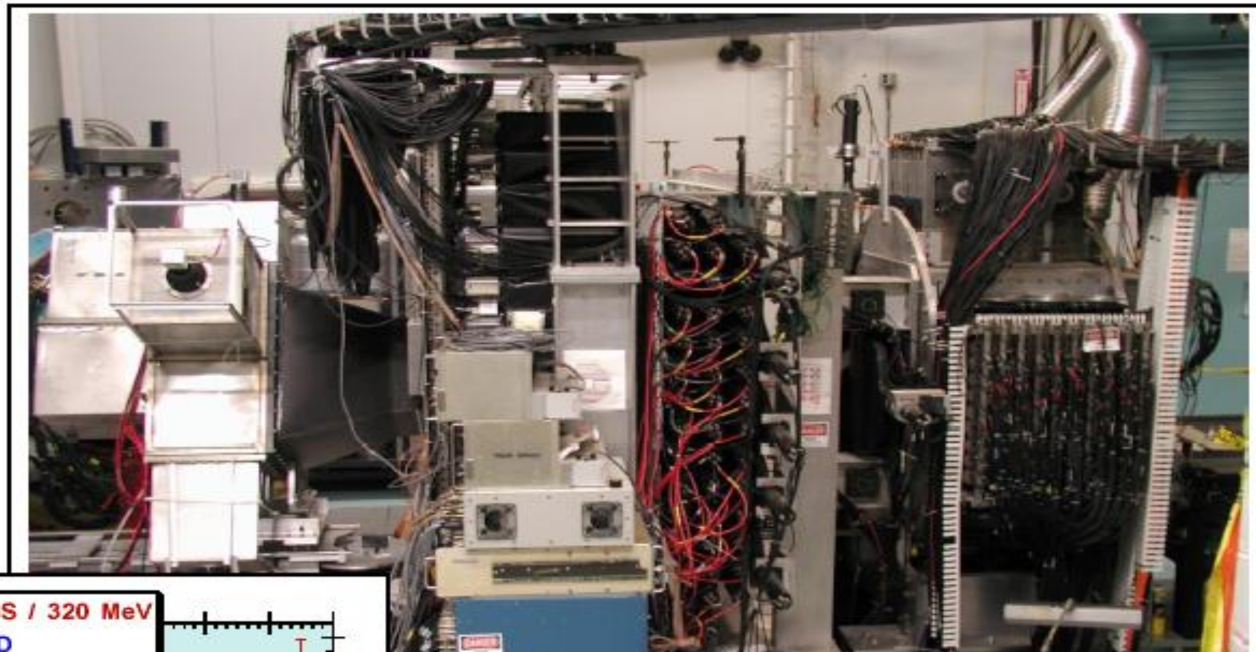
GDH integral vs. energy

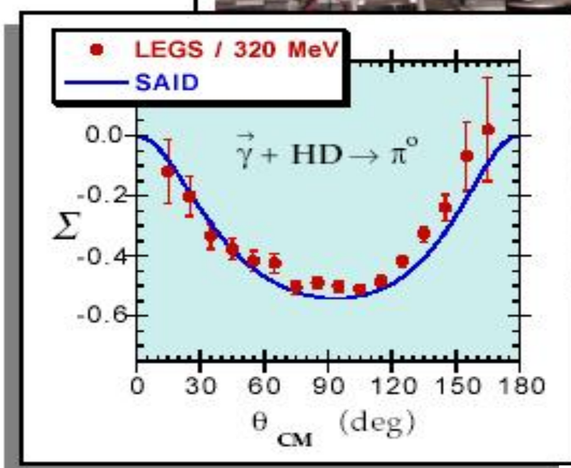
Measurements for neutron do not exist!

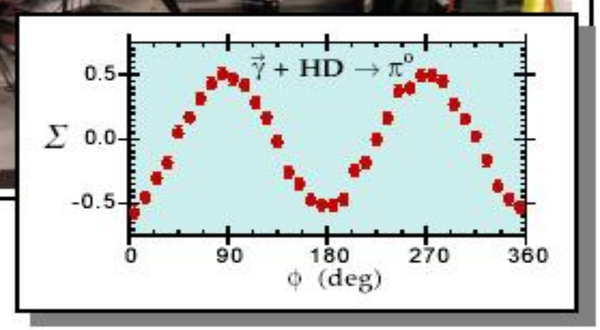
Cross Section of SASY (Spin ASYmmetry Detector)
with TPC and Superconducting Solenoid



LEGS 4π Detector







LEGS TPC Design Requirements

An essential element of SASY providing

- $\pi^{\pm}$ charge separation
- increased angular coverage
- improved resolution

Design is eased by

- low event multiplicities (≤3)
- low event rates (≤1 kHz)

Design is complicated by

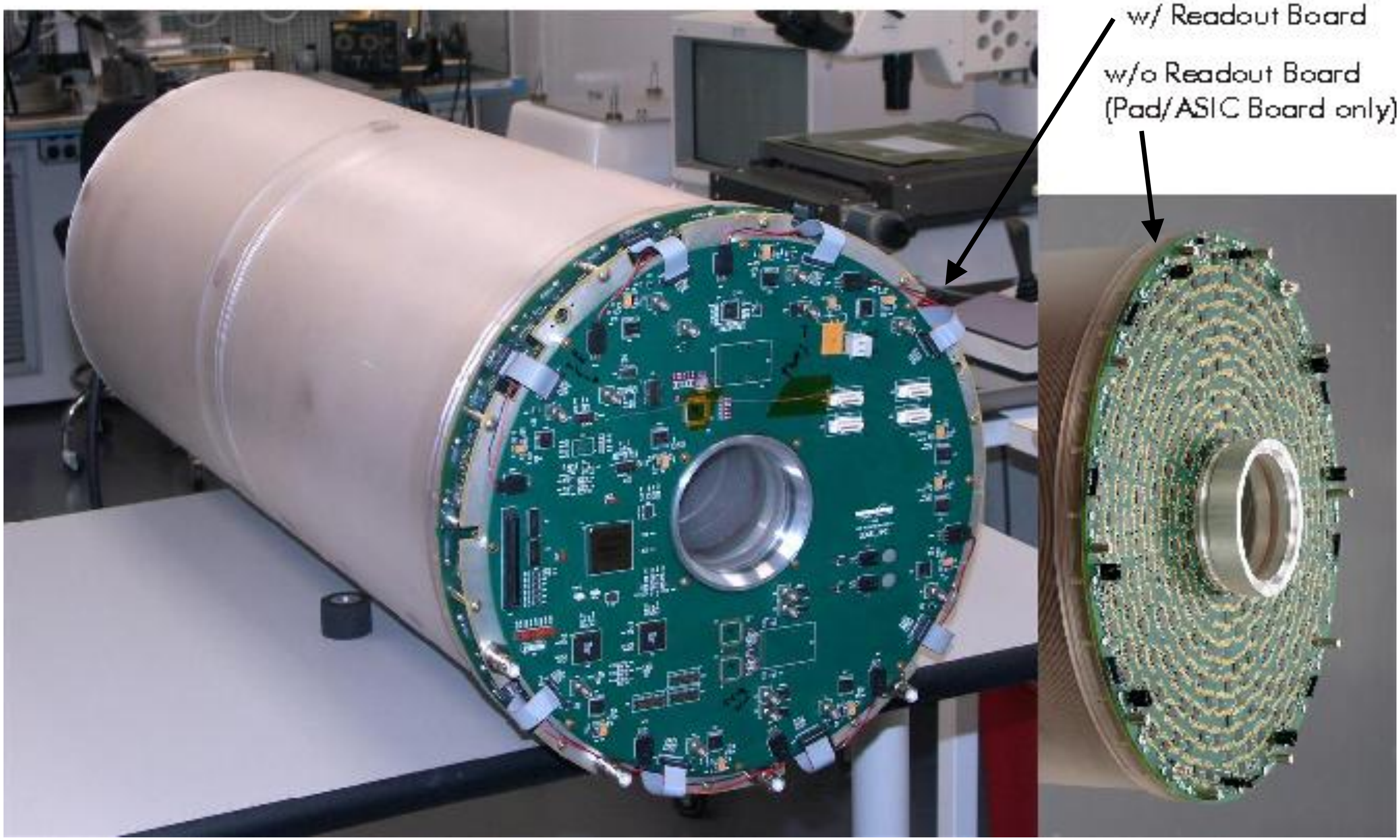
- small size to fit in XTAL Box (pad density is 17x that of Star TPC)
- low mass to allow γ detection (0.4 RL)

TPC - Key Features and Parameters

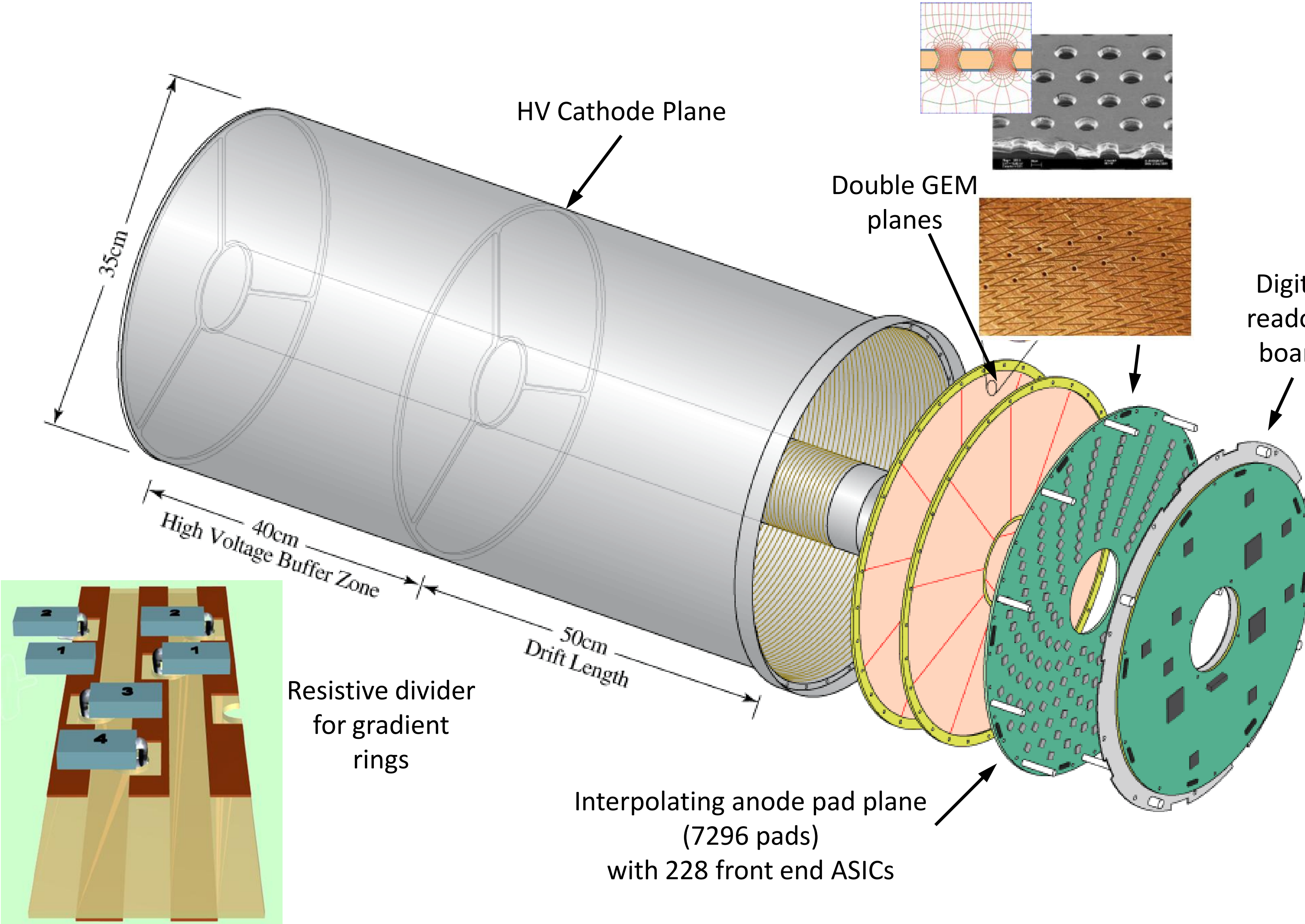
- Dimensions: ϕ8.7cm ID x ϕ35.7cm OD x 50cm active length
- Angular coverage of reactions from target: $20^o < \theta < 155^o$
- Maximum magnetic field: 1.95 T
- Single sample per channel per trigger - designed for low rate (~1 kHz), low multiplicity (~3) environment
- Double GEM amplification, *gas gain ~1600*
- Drift field ~ 245V/cm (12.5kV high voltage), total drift time ~ 6 μs (80 μm/ns) with filling gas of Ar + 20% CH_4
- Interpolating zigzag anode pad plane, ~200 µm x-y resolution for stiff tracks; *Pad density >10 times higher than in previous large TPCs*
- Readout channel count: *7296 channels of charge and time*
- Customized ASICs, 32 channels per chip, 40mW per chip, *10+6 W total*
- Electronic noise <*250e, 500ns peaking time*, timing resolution ~ 5-15 ns
- 8 set dual ADCs digitize the pedestal suppressed and serialized data streams: worst case event processing time <500 μs

Assembled TPC

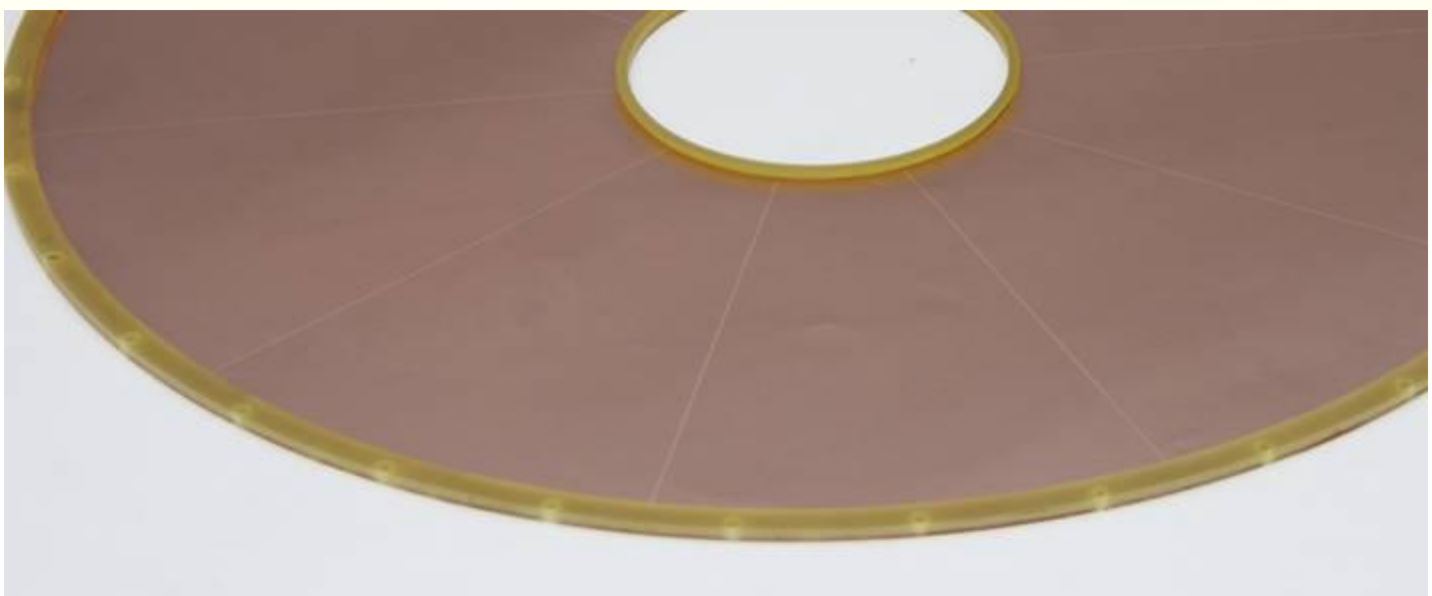
viewed from readout end



Construction of the TPC

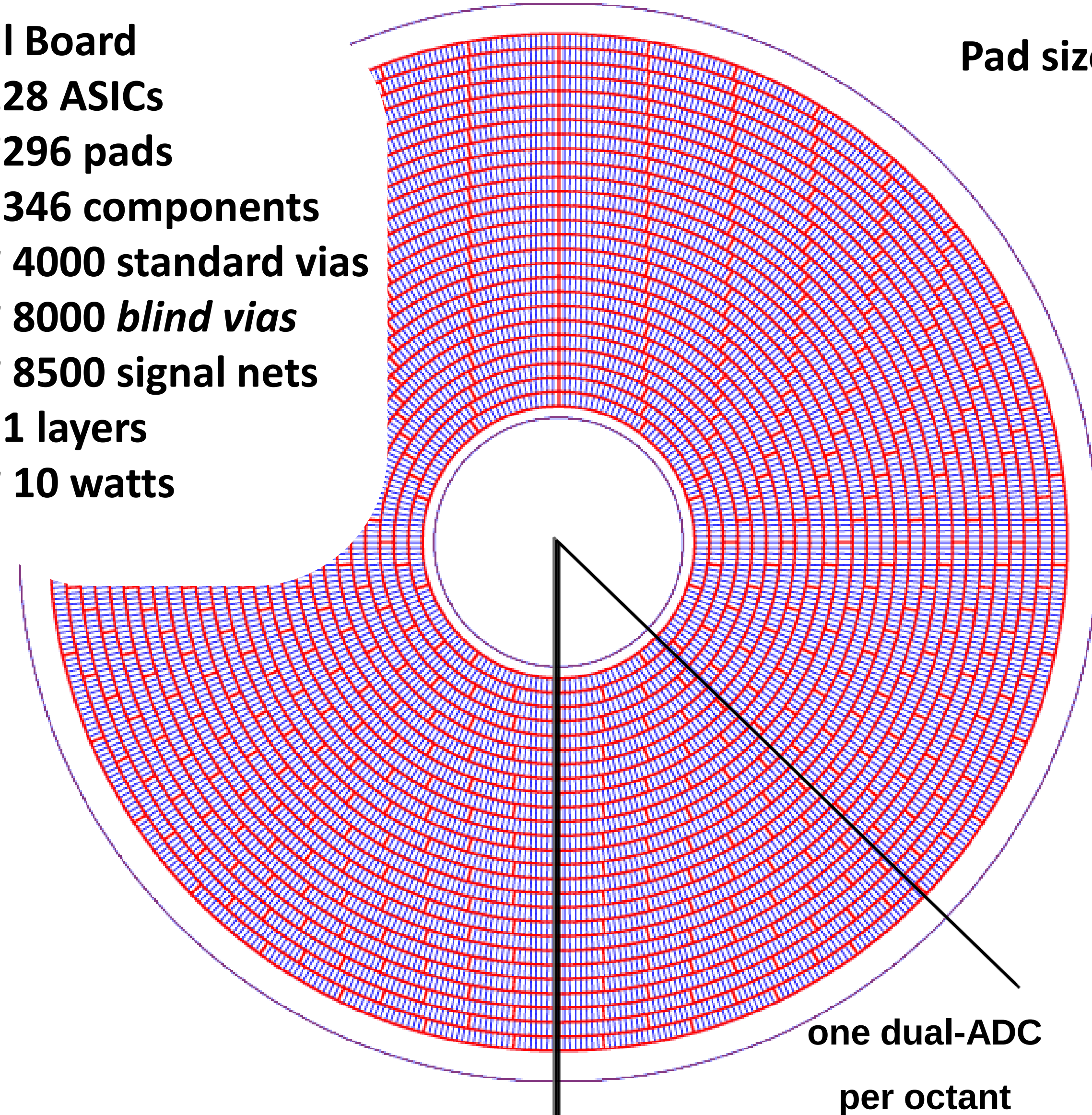


GEM Foils Mounted on Frames

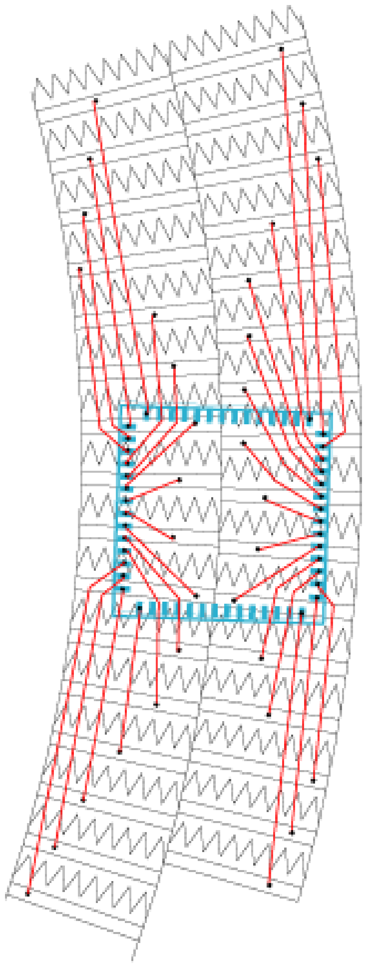


Layout of the Anode Pad Plane

Full Board
- **228 ASICs**
- **7296 pads**
- **1346 components**
- **~ 4000 standard vias**
- **~ 8000 *blind vias***
- **~ 8500 signal nets**
- **11 layers**
- **~ 10 watts**



Pad size: ~2mm x 6mm in 22 rows



Application Specific Integrated Circuit (ASIC) for LEGS TPC

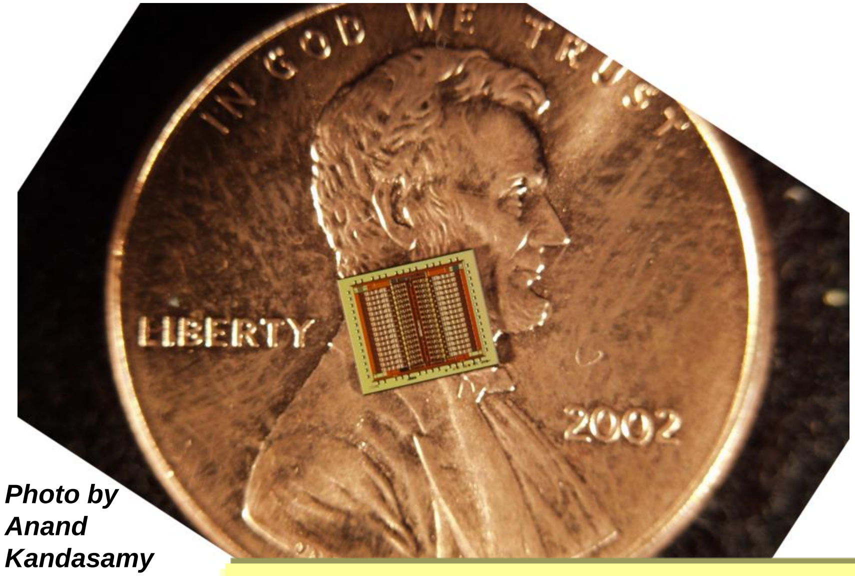
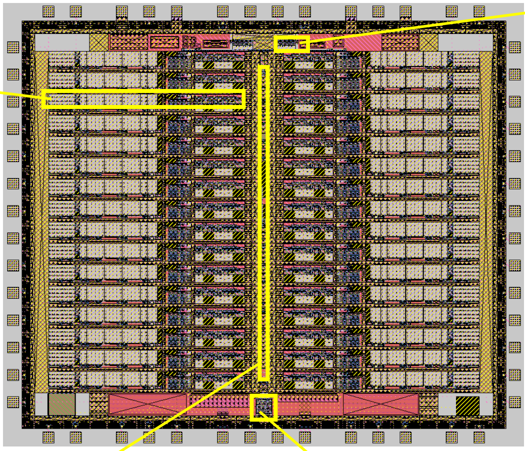
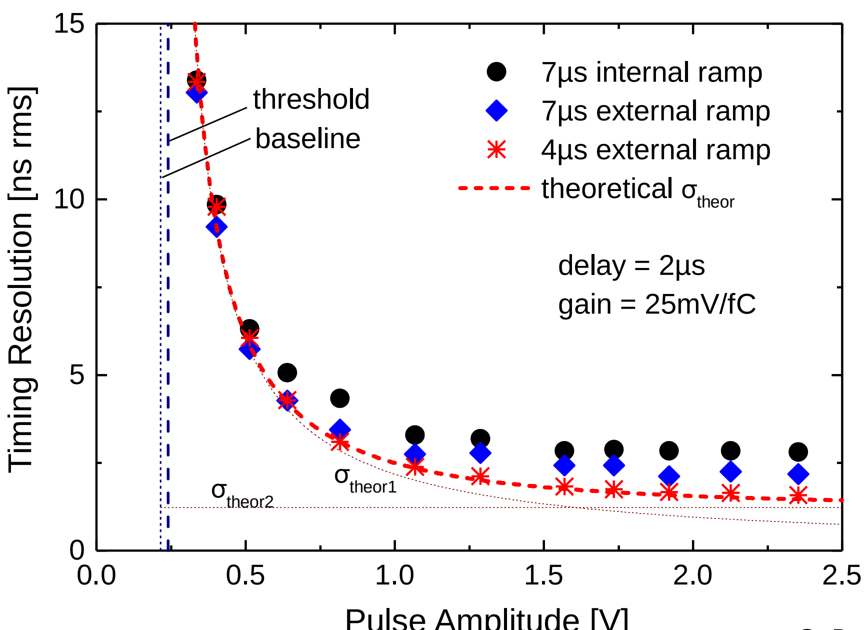


Photo by Anand Kandasamy



***7296* low-noise channels : *228* front-end ASICs**

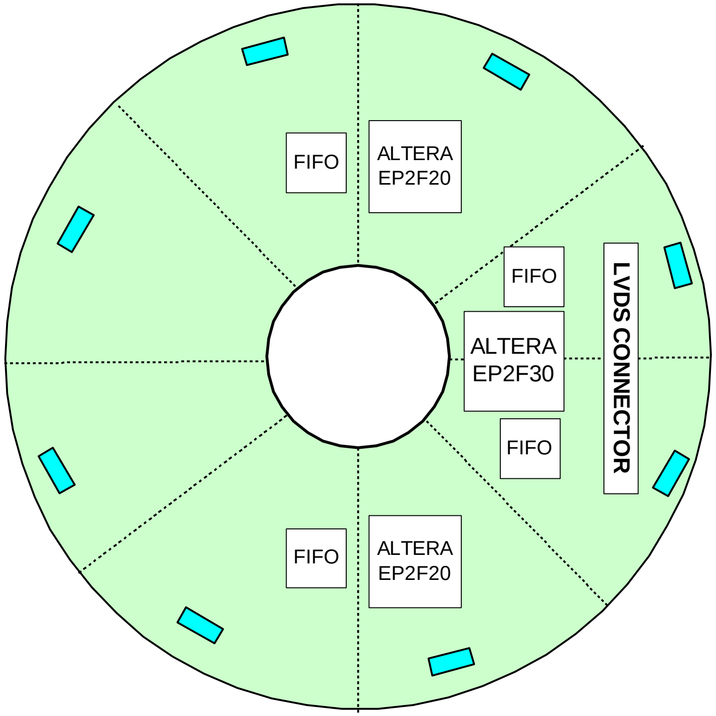
***0.25µm* CMOS**
3.6x3.1 mm²



- **32-channels**
- **1.3mW / channel**
- **Peak detection**
- **Timing Detection**
- **ENC ≈ 100+25/pF e^- rms**
- **Timing Resolution <10 ns rms**
- **Neighbor capture logic**
- **Sparsified readout**

G. De Geronimo, J. Fried, B. Yu (Instrumentation Division/BNL) – C. Thorn (LEGS/BNL)

Digital Data Acquisition System



PCI CARD

- **PCI Version 2.1 compliant**
- **Altera Programmable Logic**
- **3.3 or 5 volt compatible**
- **External clock speed up to 80 MHz**
- **Two independent DMA channels**
- **PCI data transfers up to 100MB/sec**
- **Two 1MB memory banks**
- **36 bit bi-directional LVDS lines nibble selectable**

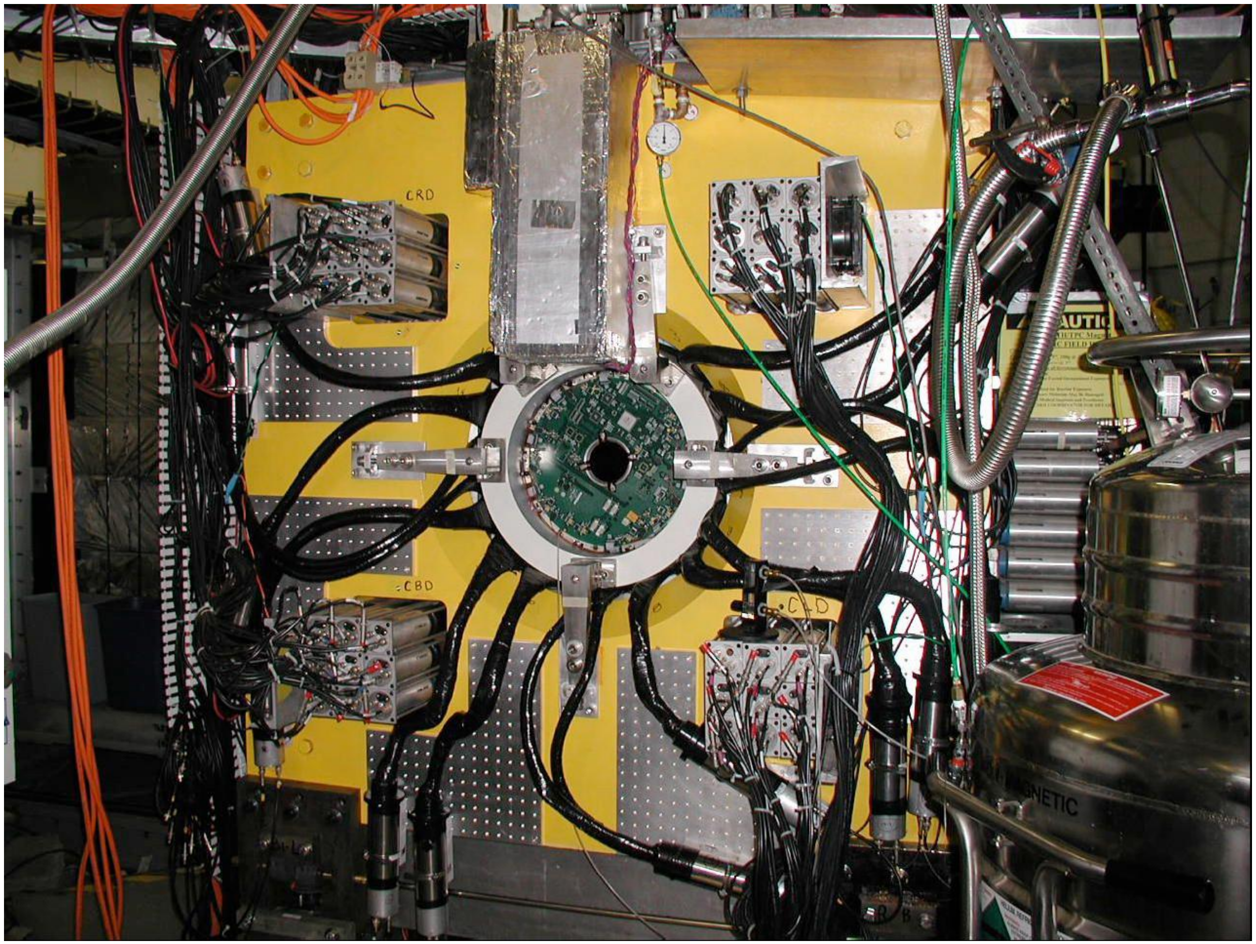
LEGS TPC DIGITAL INTERFACE READOUT BOARD

Altera Programmable Logic
2Mbit dedicated FIFO memory
Integrated system diagnostic
36 bit bi-directional LVDS lines nibble selectable

– Jack Fried

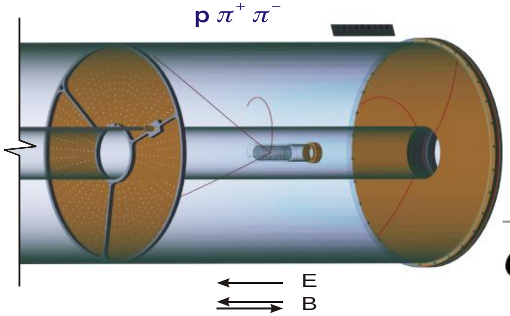
TPC Installed in XTAL Box at LEGS Beamline at NSLS

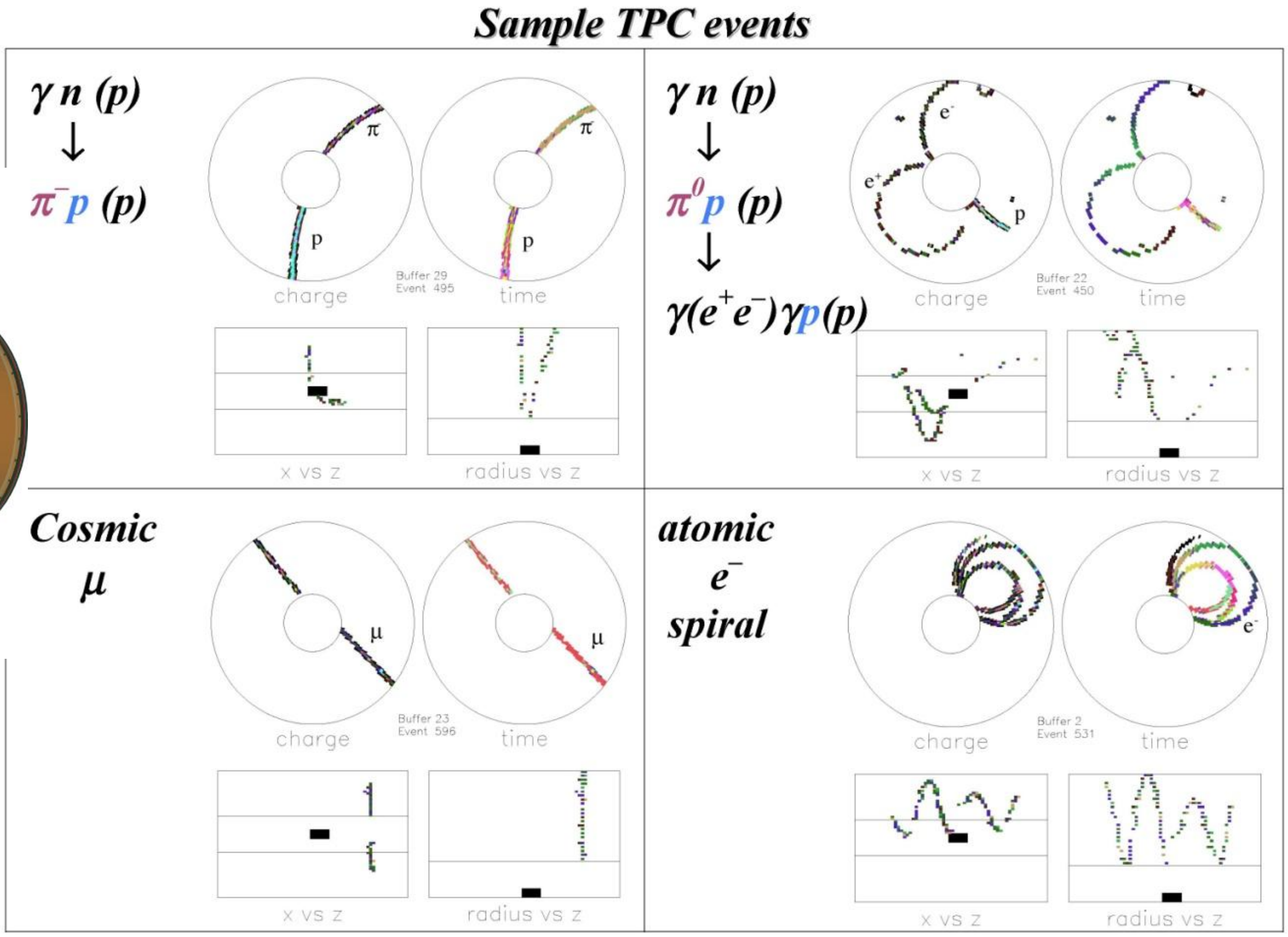
View from upstream end with HD Ice cryostat removed



Typical Track Images

projected in planes transverse and parallel to TPC axis

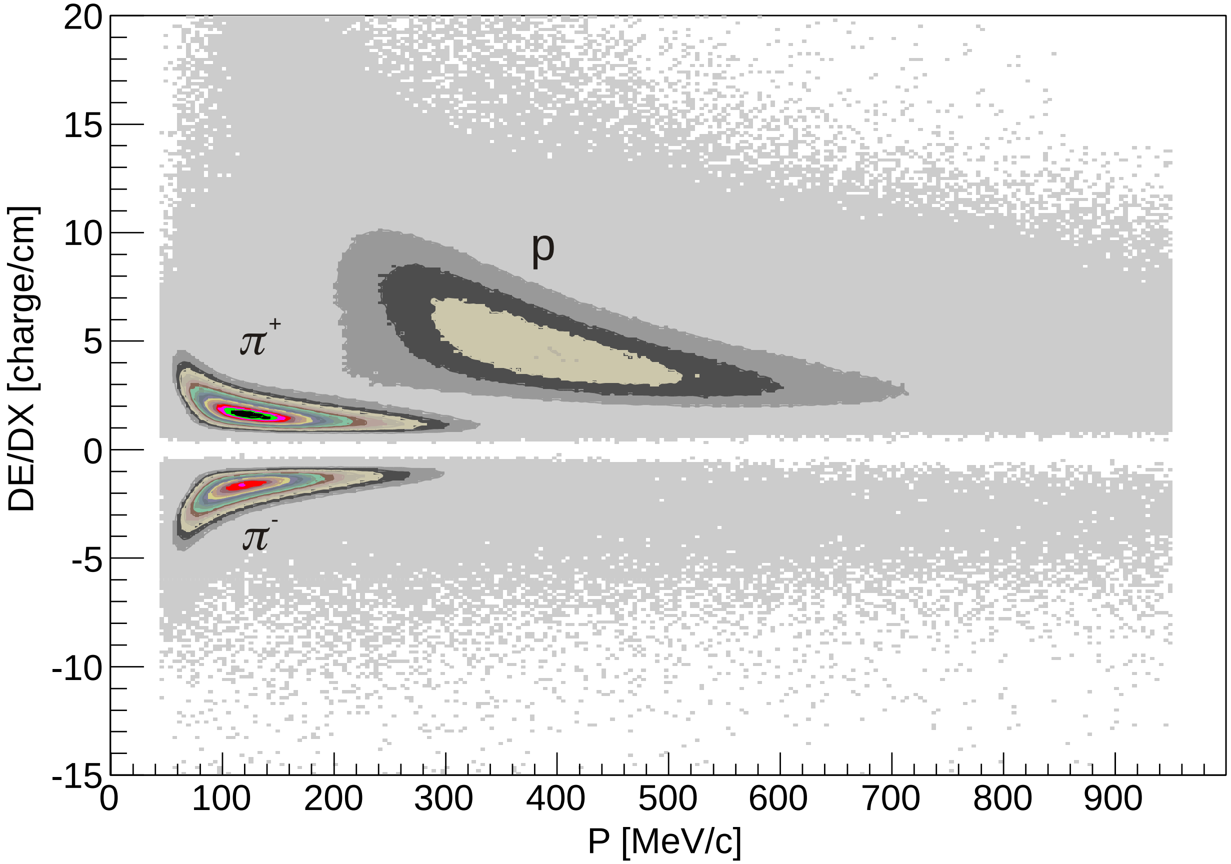




Particle Identification in LEGS TPC

$\gamma p \rightarrow \pi^+ n$ $\gamma n \rightarrow \pi^- p$

$\gamma p \rightarrow \pi^0 p$ $\gamma n \rightarrow \pi^0 n$

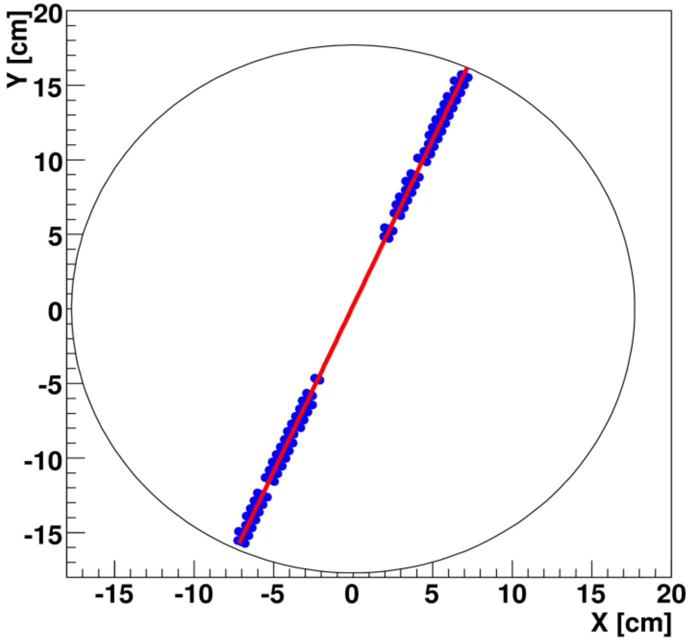


High energy cosmic tracks in TPC

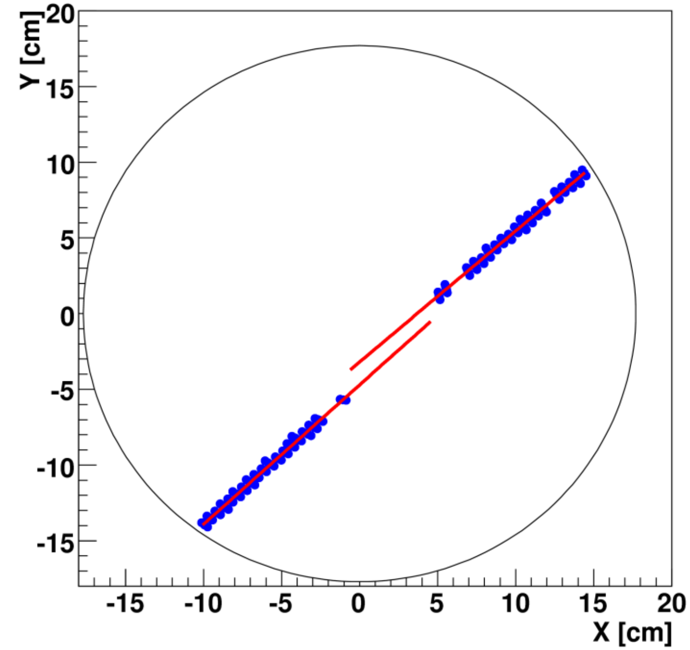
Radial component of E creates tangential force on drifting electrons

F=e(E + v x B)

$Z_{DRIFT} < 5$ cm

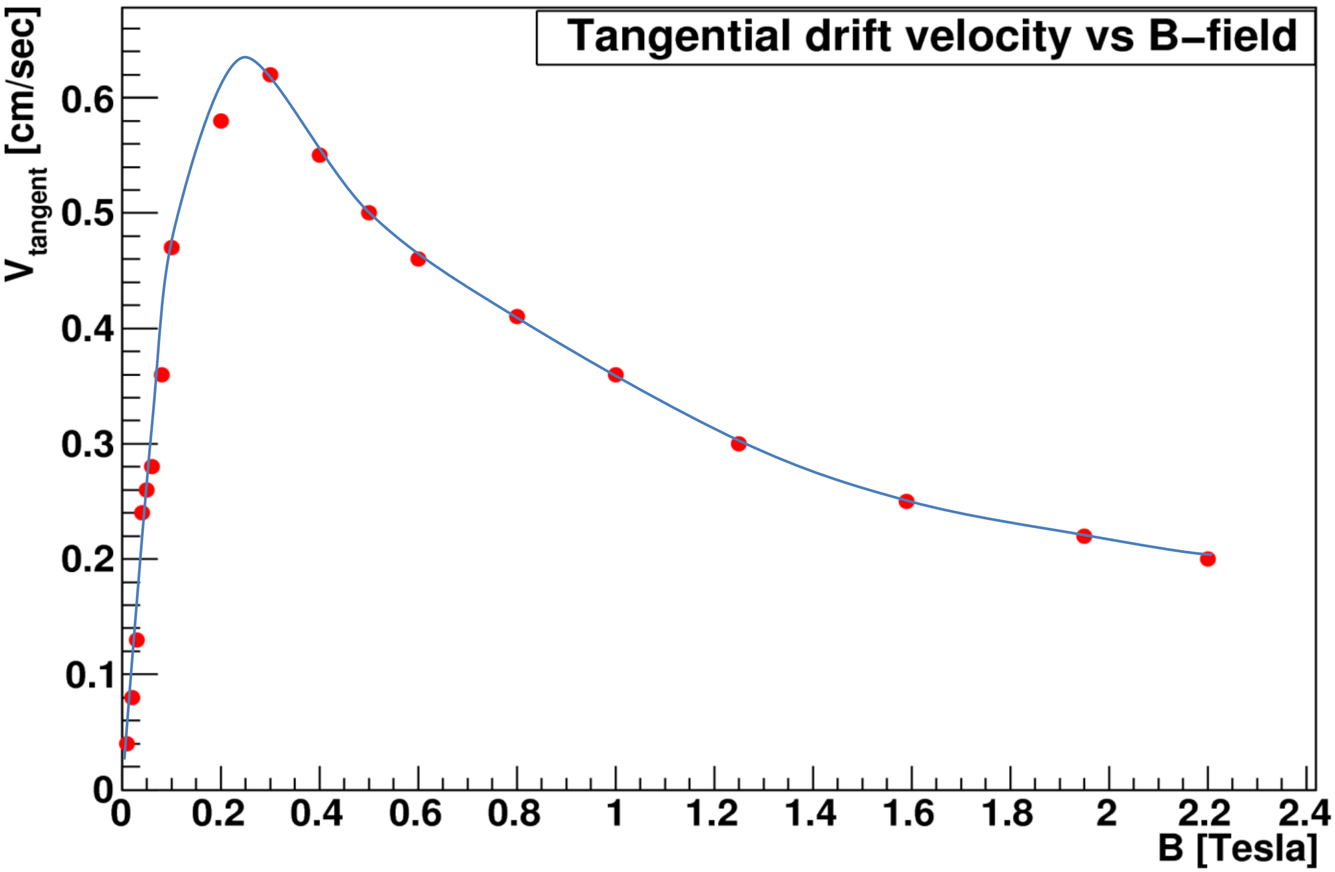


$Z_{DRIFT} > 45$ cm



Tangential Component of Drift Velocity

for constant radial component of E
in Ar + 20% CH_4
computed by MagBoltz
E =245 V/cm @ 1º to B

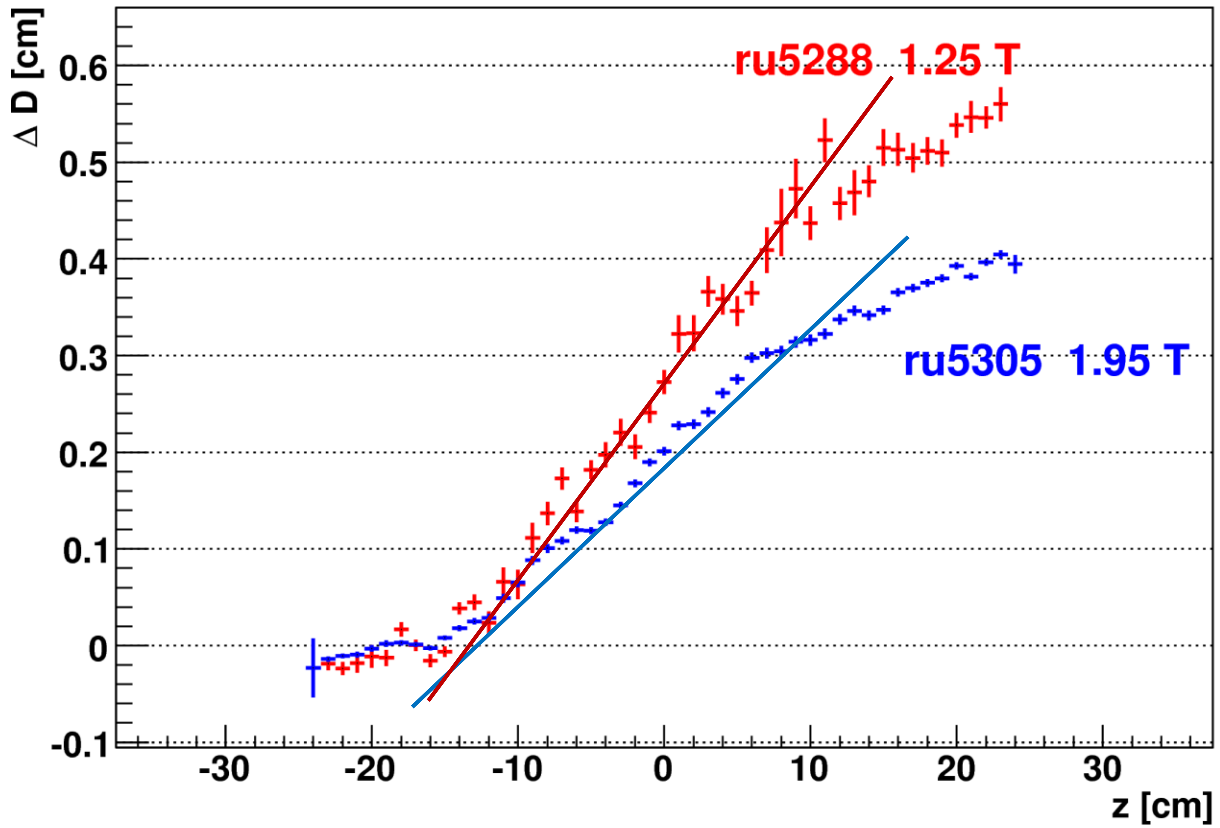


Cosmic Ray Tracks

"Half-Track" mismatch distance

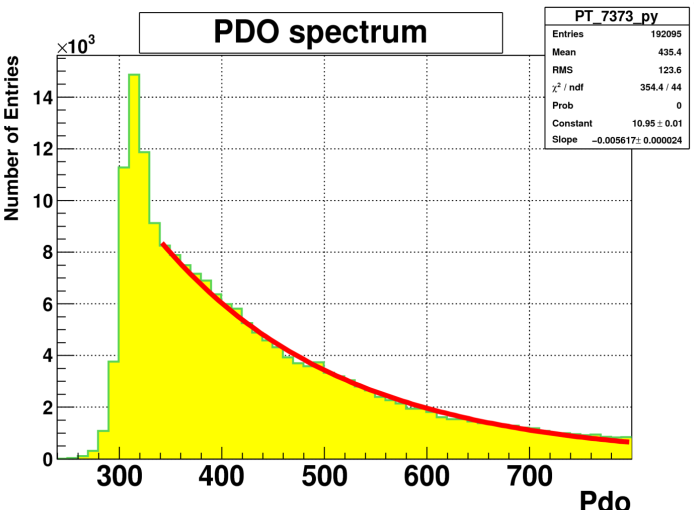
vs. drift distance

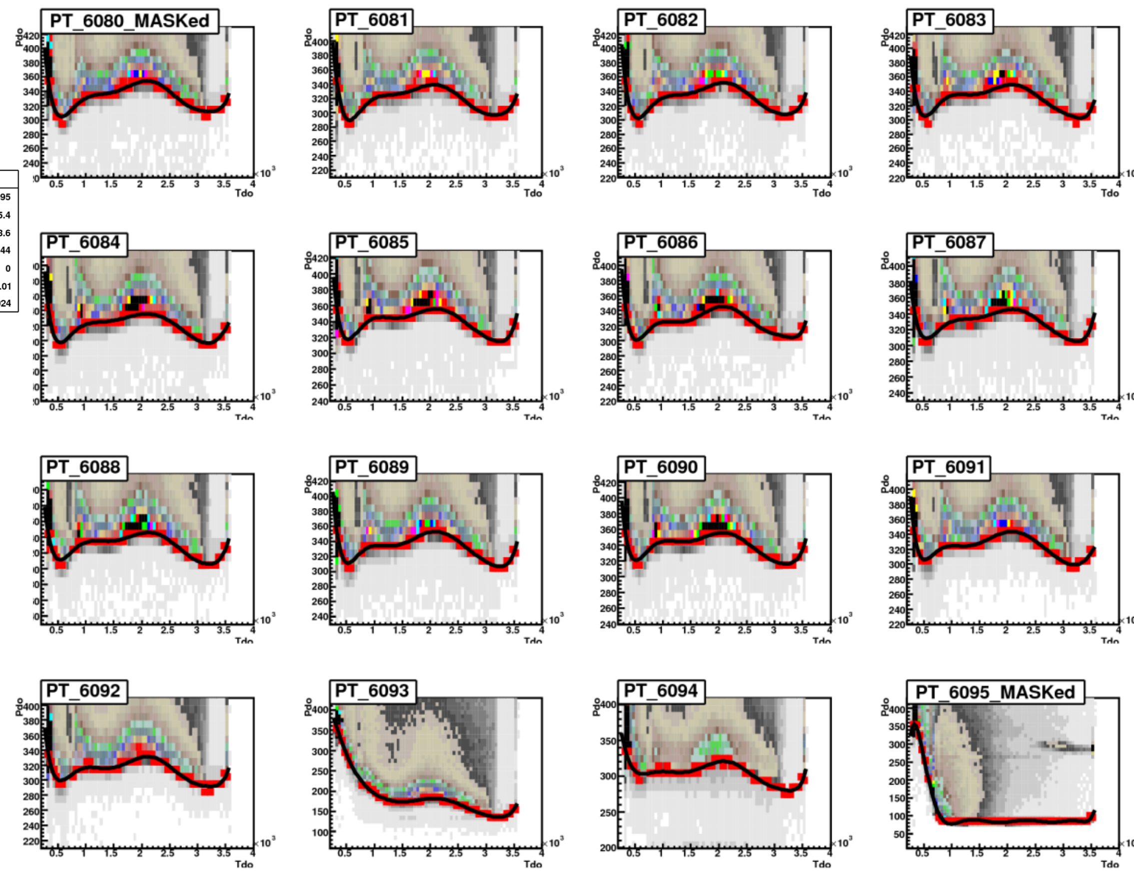
for E_r = 5 V/cm



Charge pedestals depend on Time after Trigger

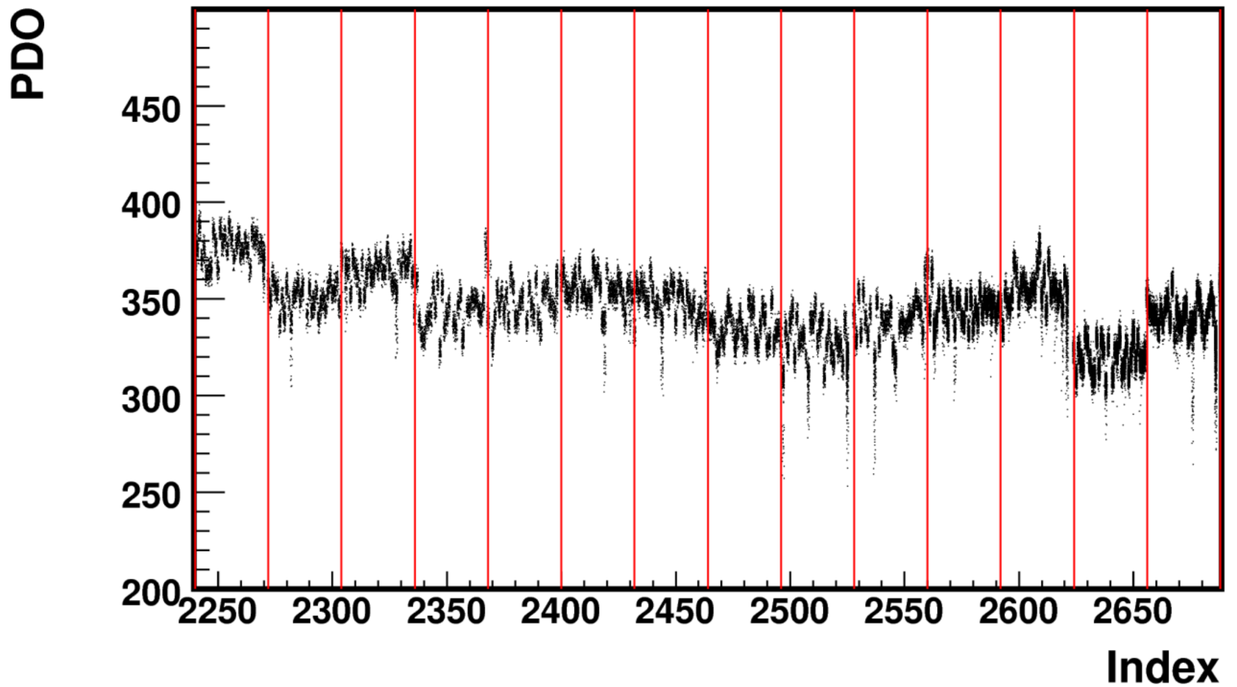
Coupling of timing (TDO) output into charge input?





Chip-to-chip variation of charge pedestals

for 14 ASICs



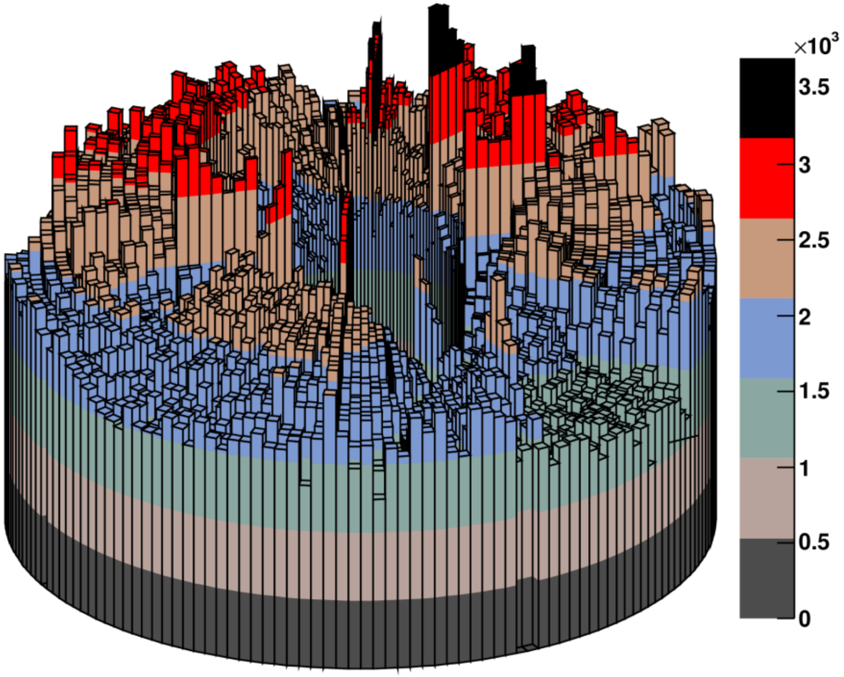
Pad-by-pad Gains Determined with X-Rays

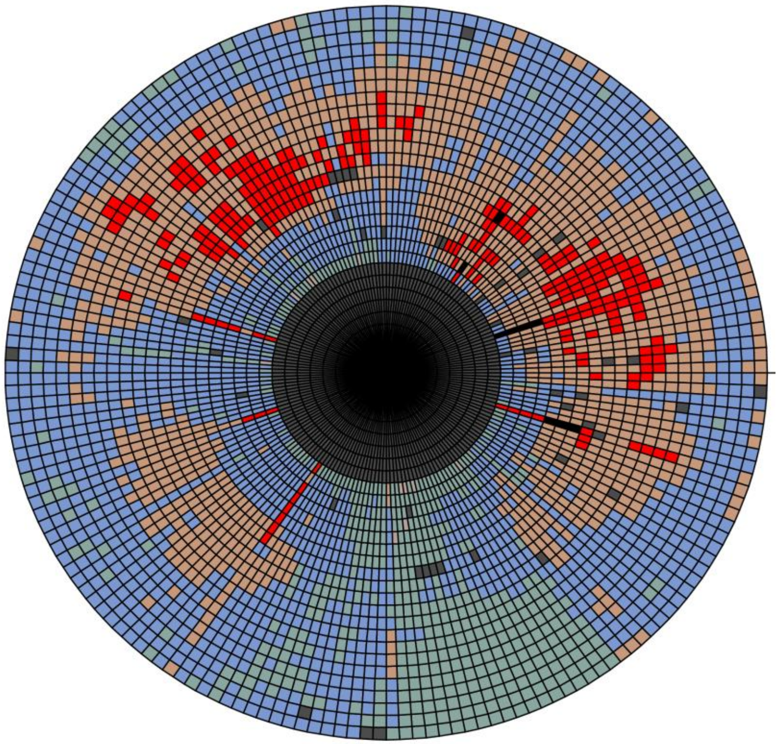
Measured with DVGEM = 400V

Non-uniformity of GEM and charge amplifier is noticable

One GEM sector (out of 10) has lower gain

Sector boundary effects are visible





Pad-by-pad Gains Determined with Protons

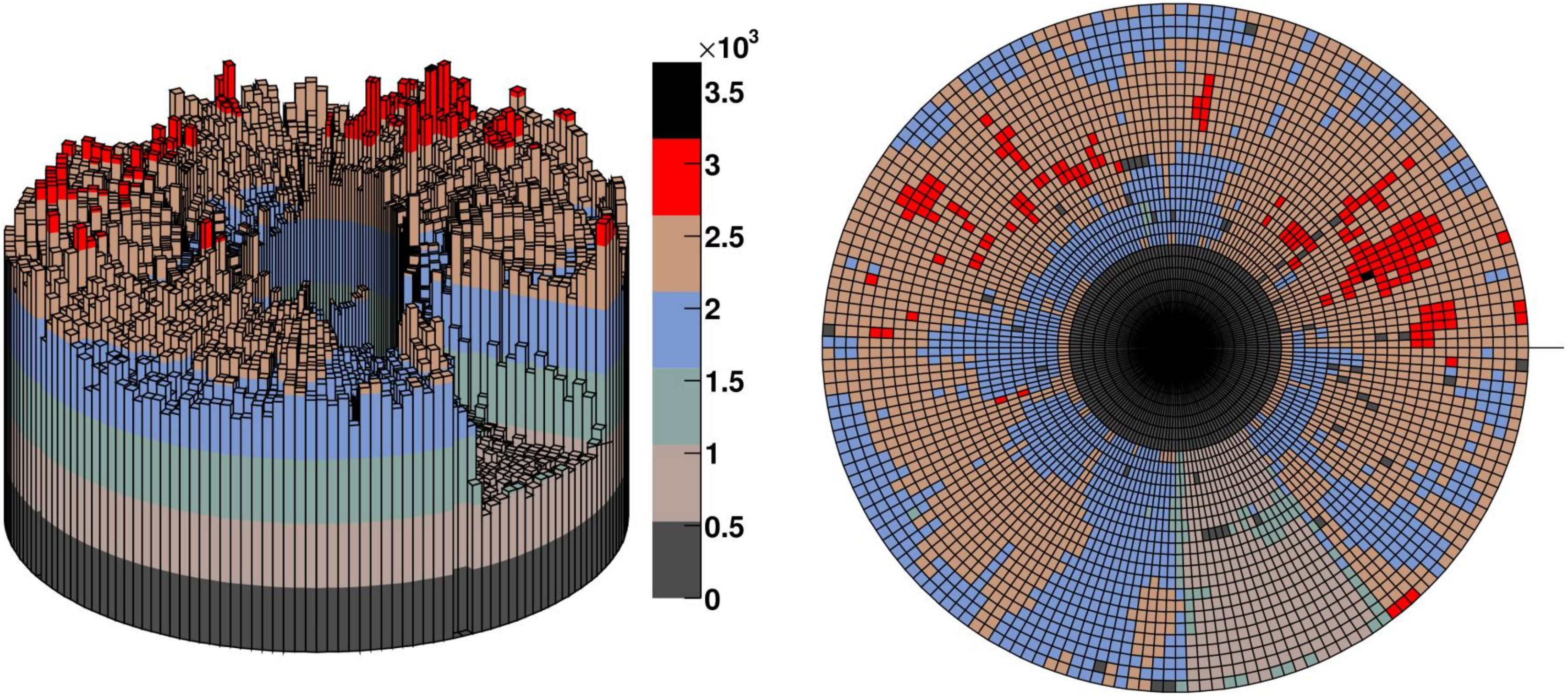
Measured with DVGEM = 388V

Calculated from dE/dx of protons with narrow cut on momentum

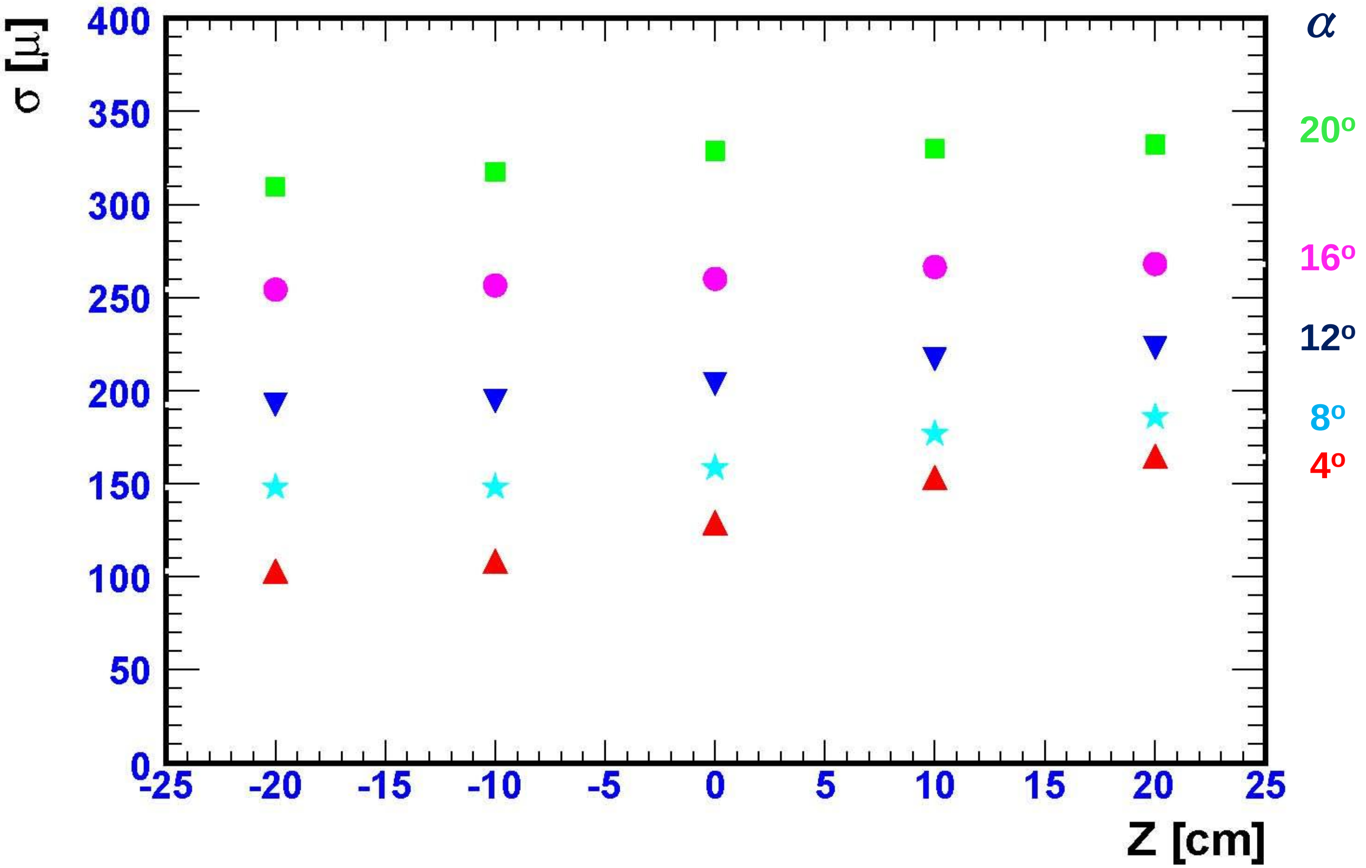
Non-uniformity of GEM and charge amplifier is noticeable

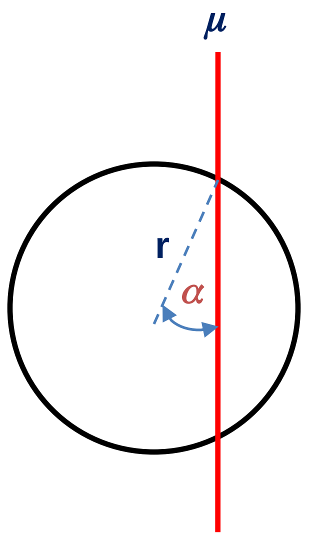
One GEM sector (out of 10) now has very low gain

Sector boundary effects are visible



Transverse Spatial Resolution
for
incidence angle on pad row

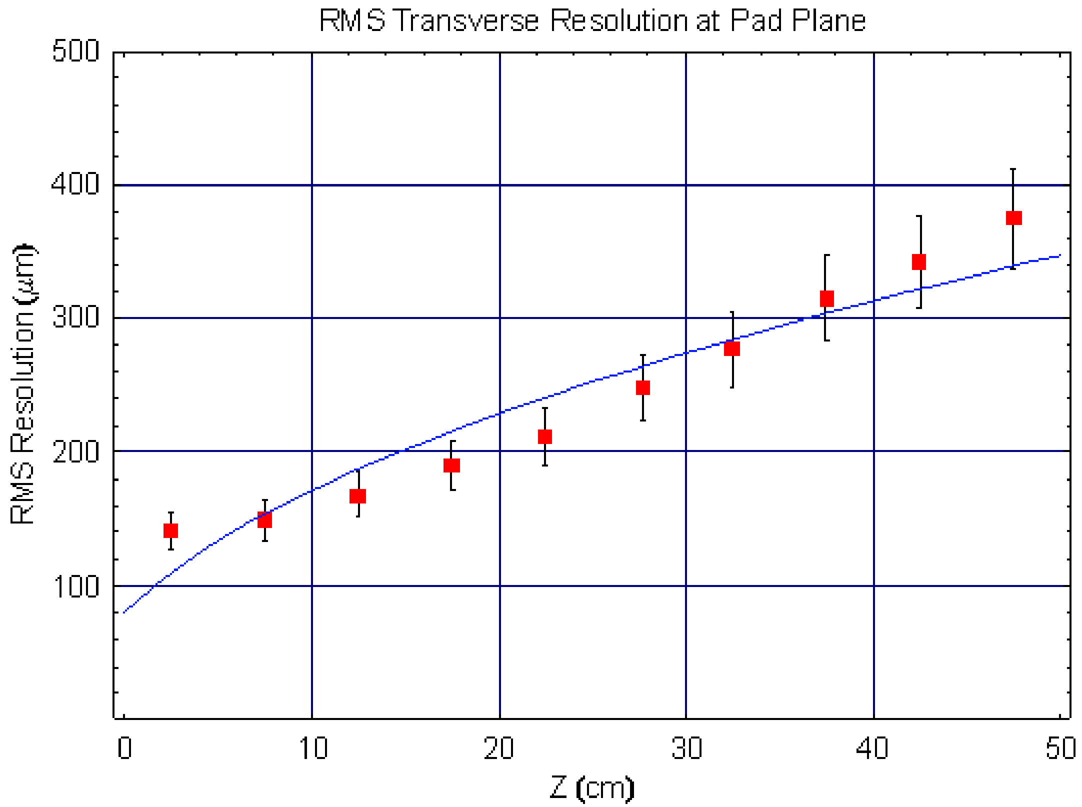




Effect of Diffusion on Transverse Spatial Resolution

Position Resolution for High Energy Cosmic Ray Tracks

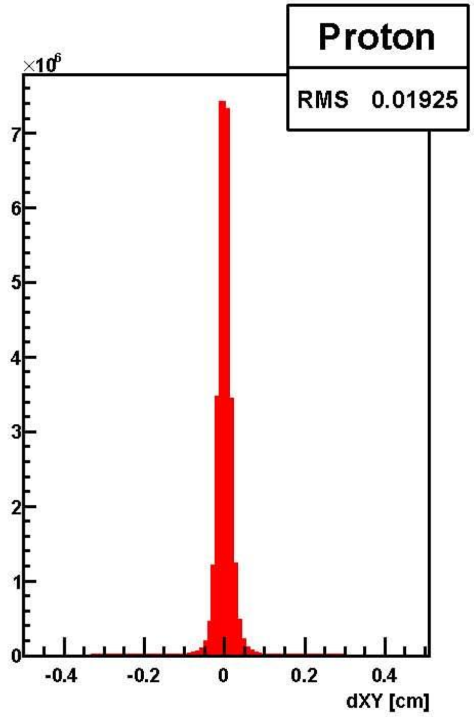
1.95 T, Ar +20% CH_4

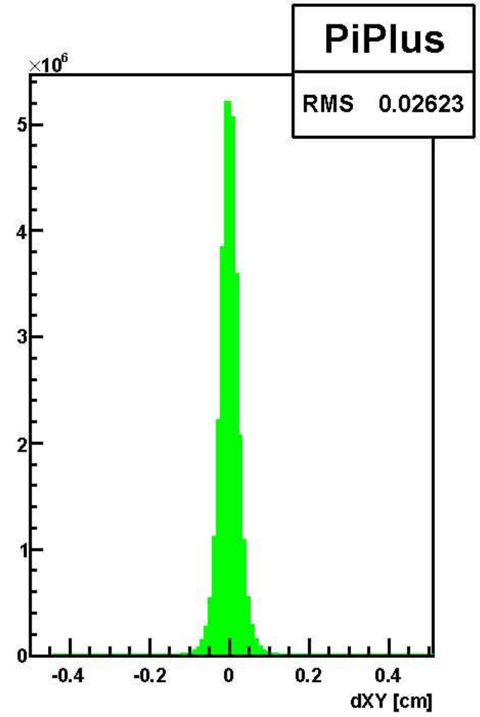


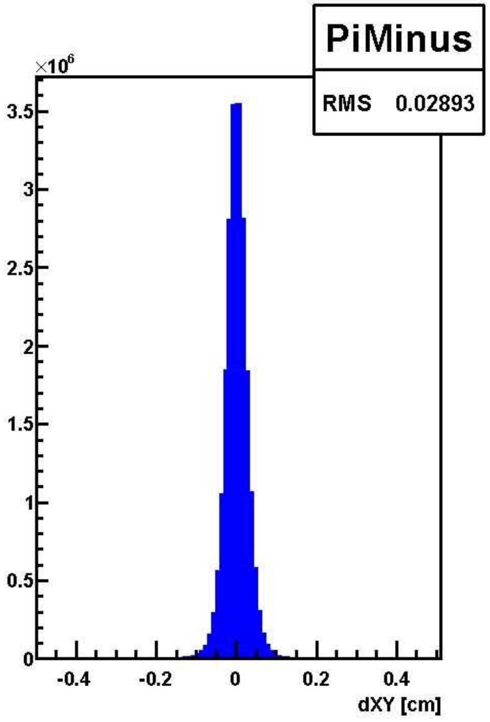
Line is $\sigma_x^2 = \sigma_0^2 + D^2 z$ with $\sigma_0 = 80\ \mu$m and $D = 48\ \mu$m/cm

Pad Plane Resolution for reaction events p, π^+, and π^-

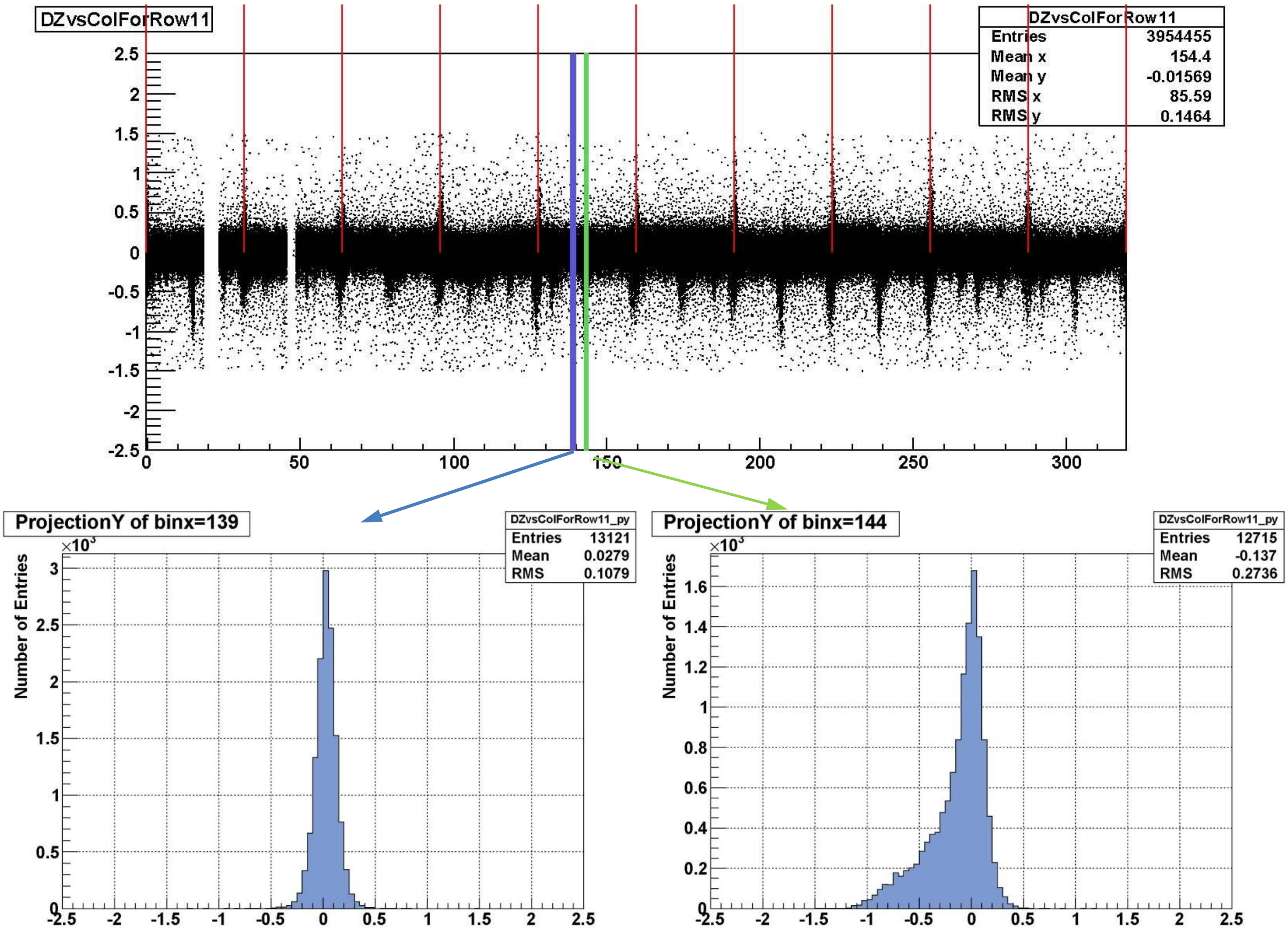
originating at the target



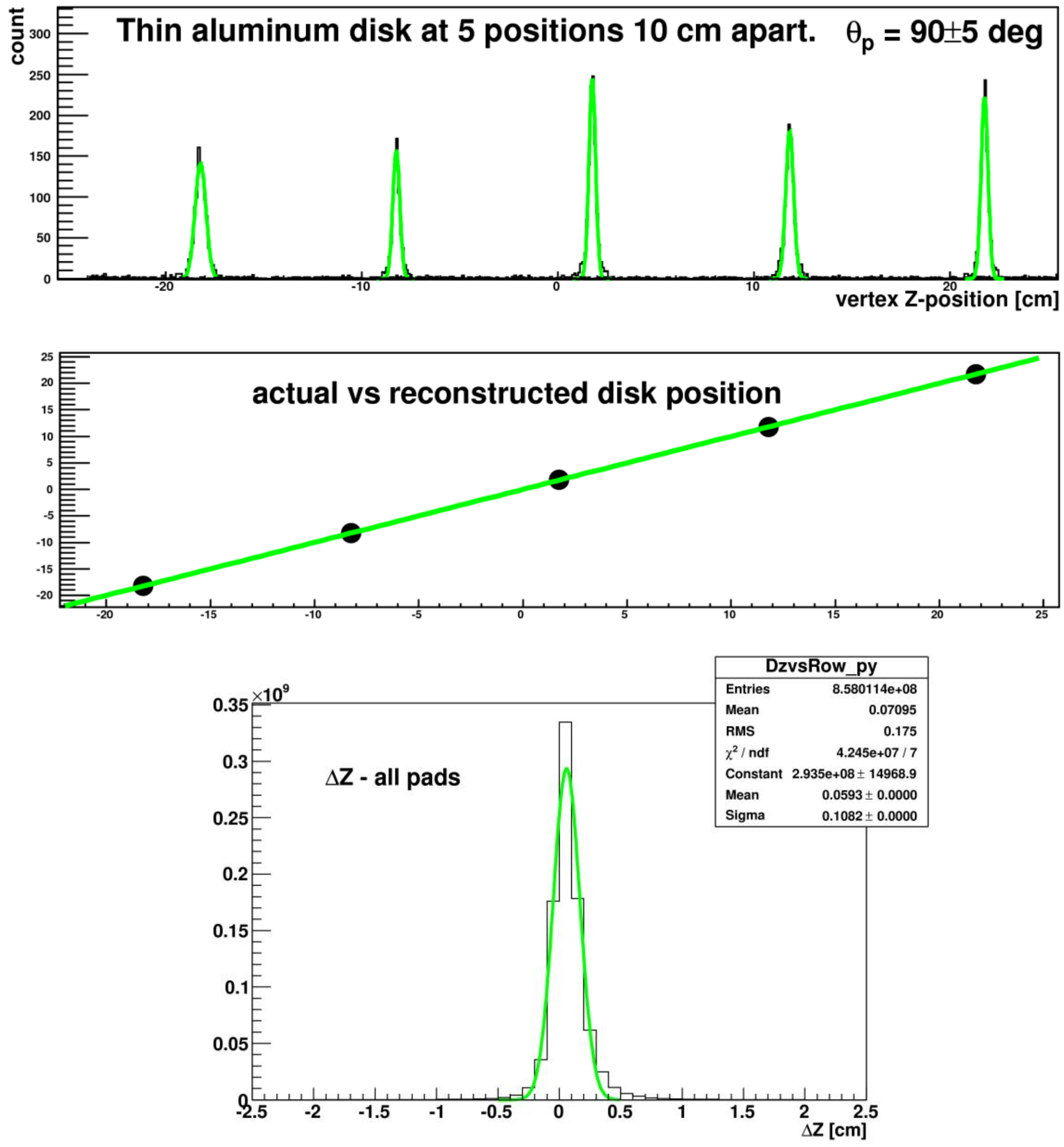




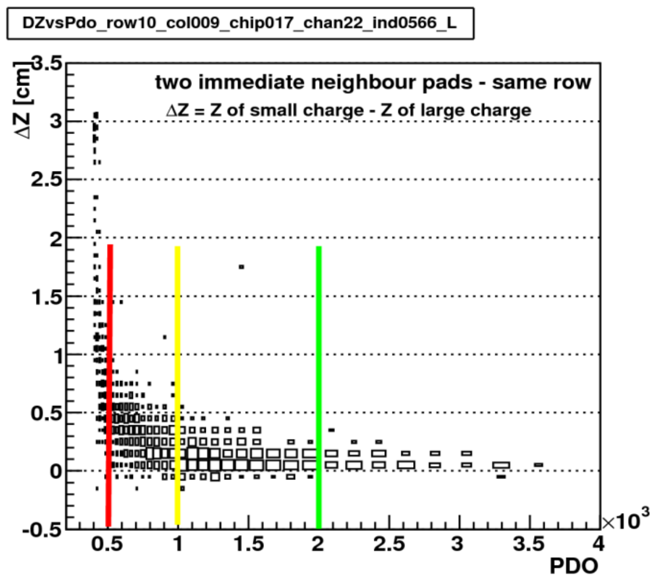
Chip-to-chip and within-chip variation of timing resolution

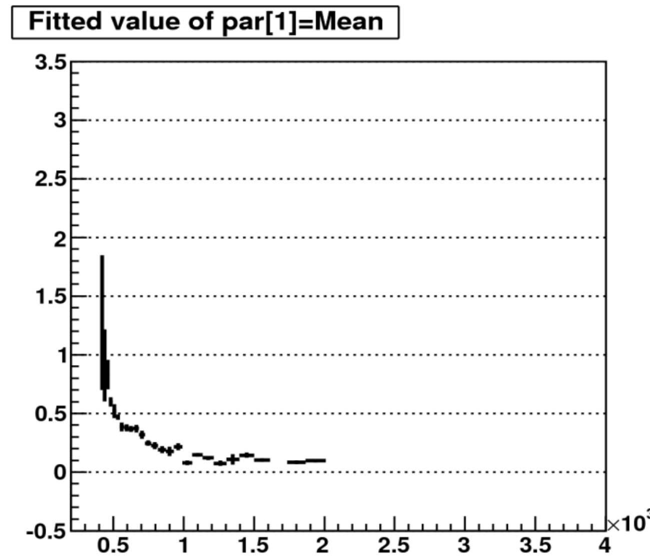


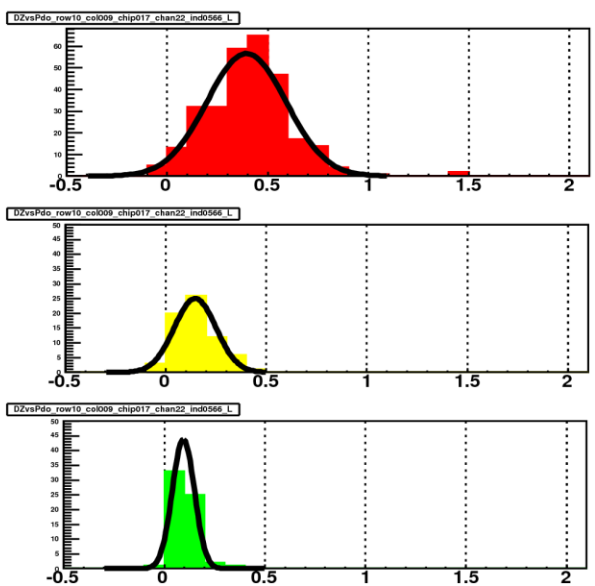
Z-Position Calibration and Resolution Measurement

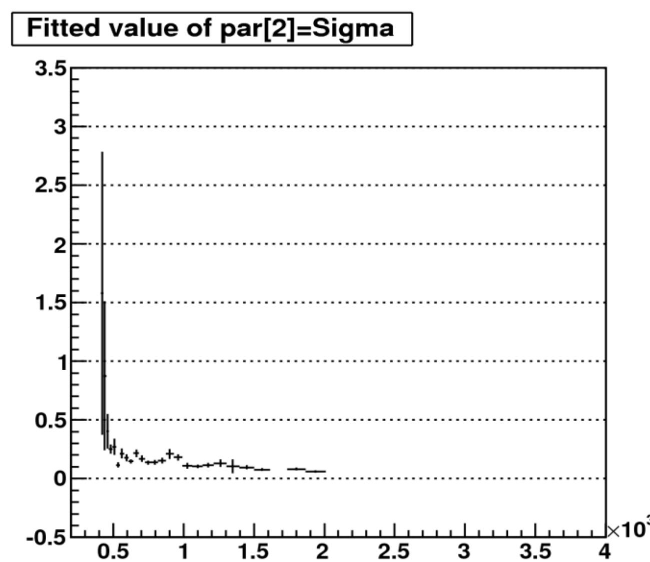


Z Position and Resolution Depends on Charge



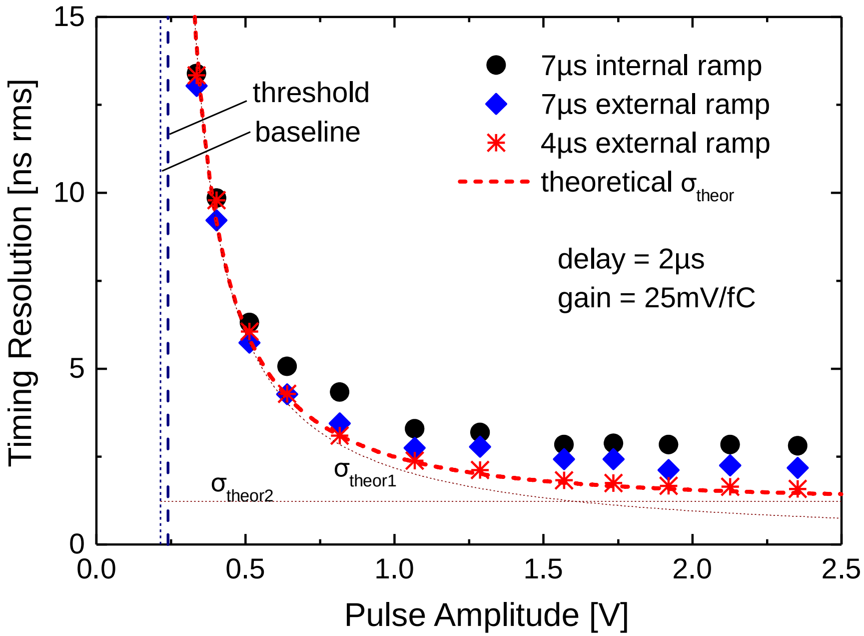




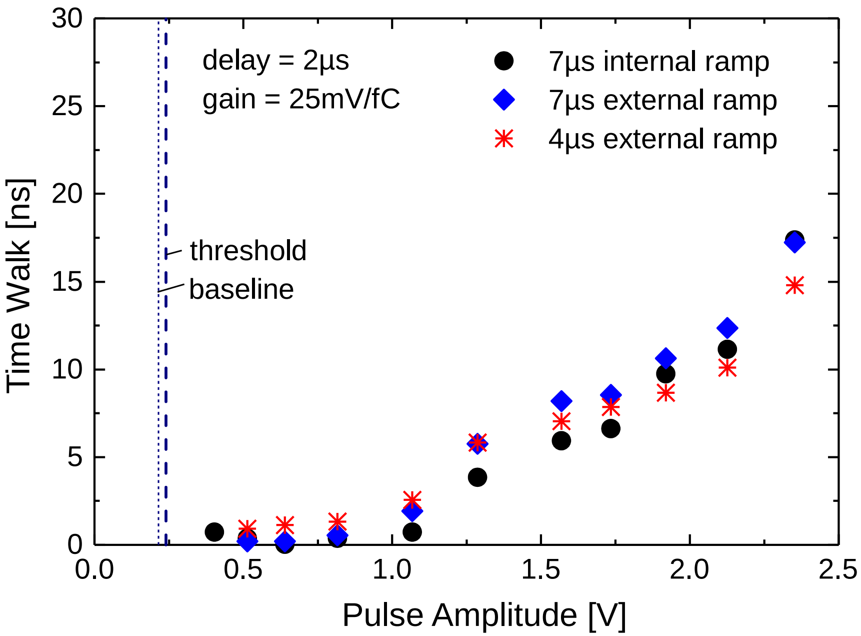


ASICs: Measured Timing Resolution and Walk

Timing Resolution vs Energy



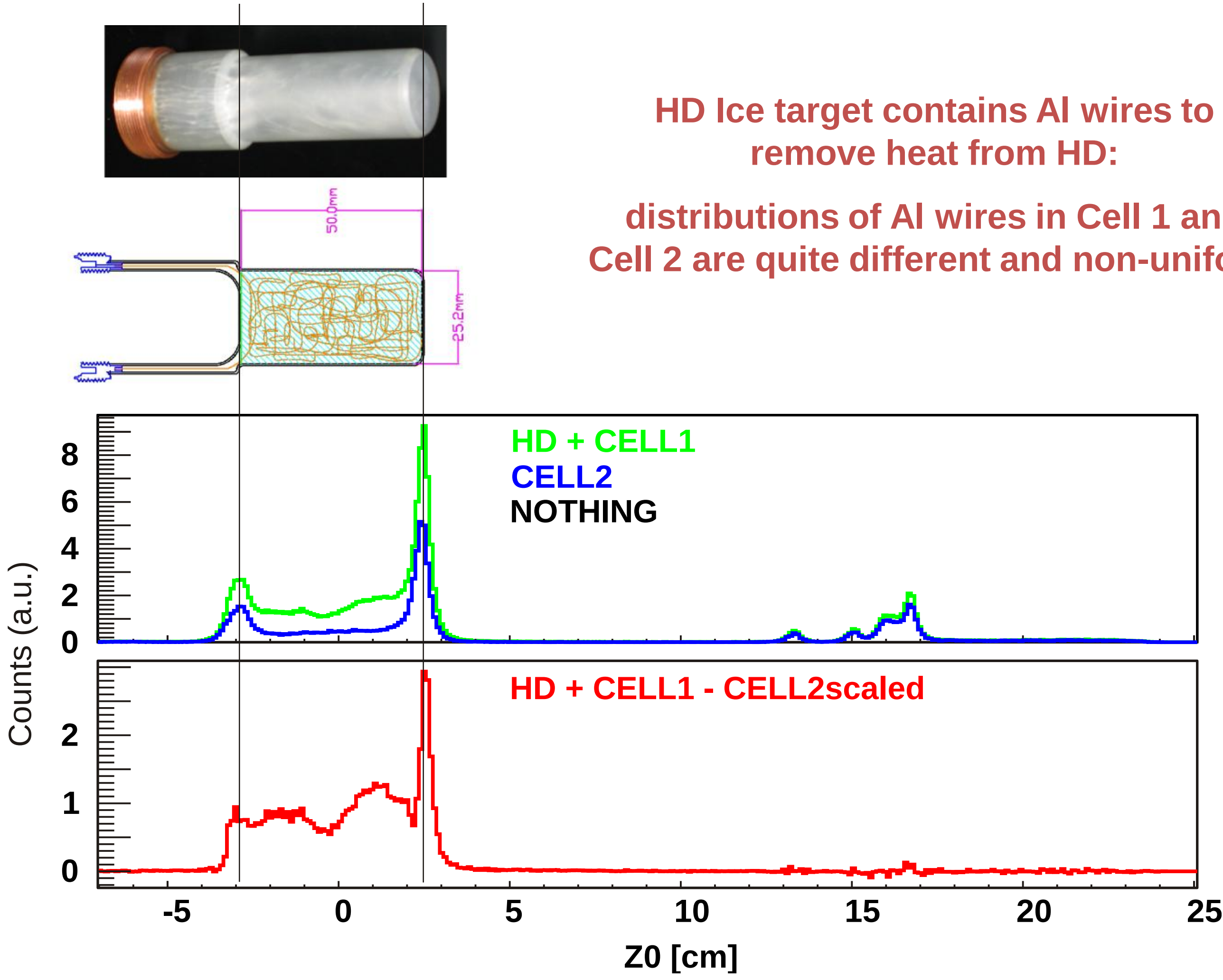
Time Walk



- G. De Geronimo

Reconstruction of HD Ice Target

by projection of proton tracks onto TPC axis



HD Ice target contains Al wires to remove heat from HD:

distributions of Al wires in Cell 1 and Cell 2 are quite different and non-uniform

Reconstructed Energy Resolution and Efficiency

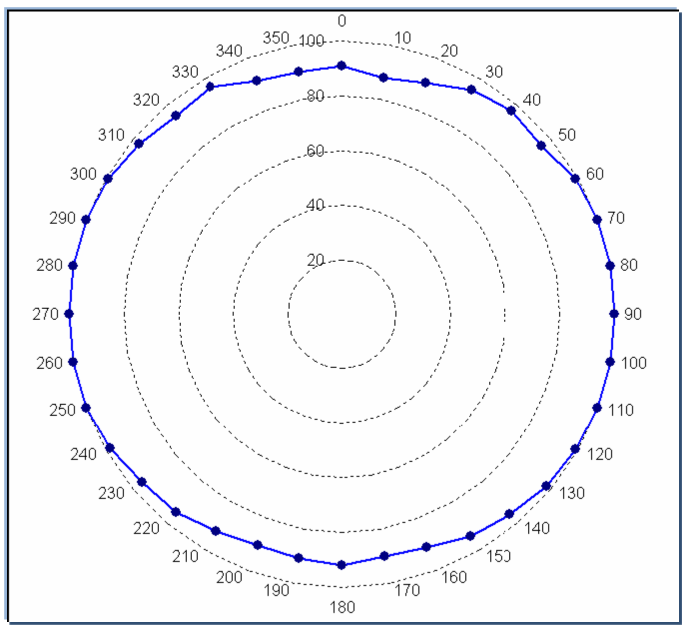
for Protons and Pions

Two-body kinematics

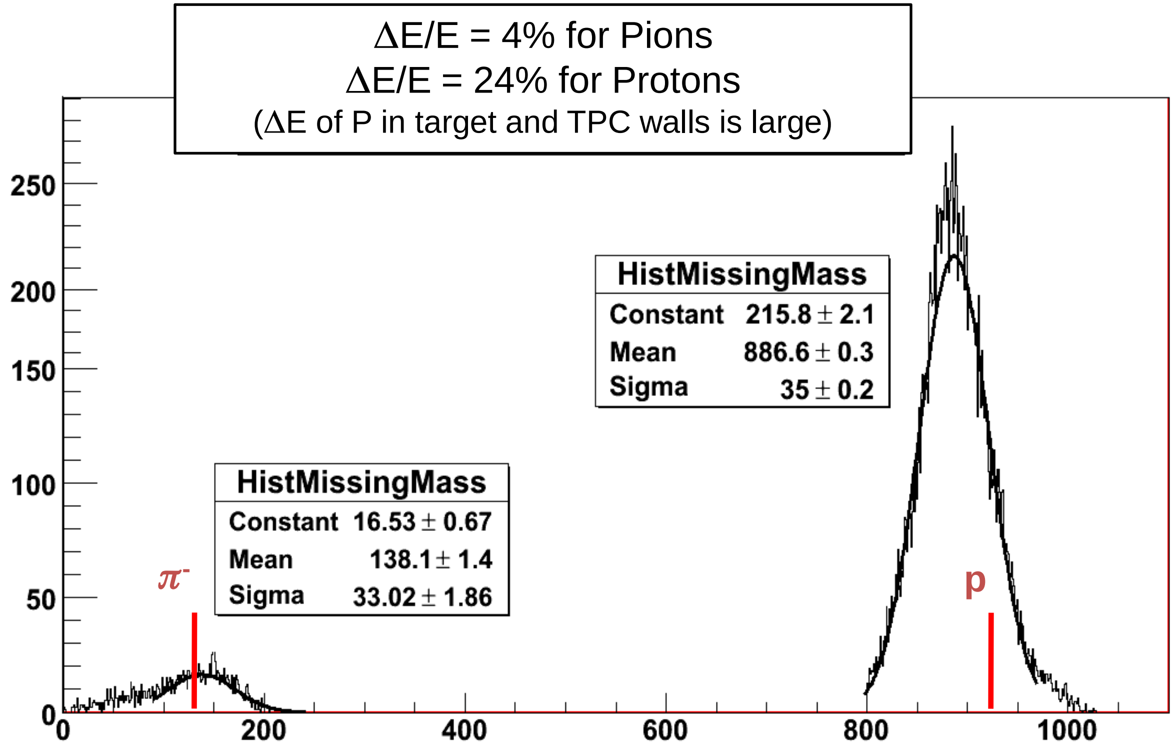
γ **+ n →p +** π^-

Redundancy of measured momenta over-determines kinematics

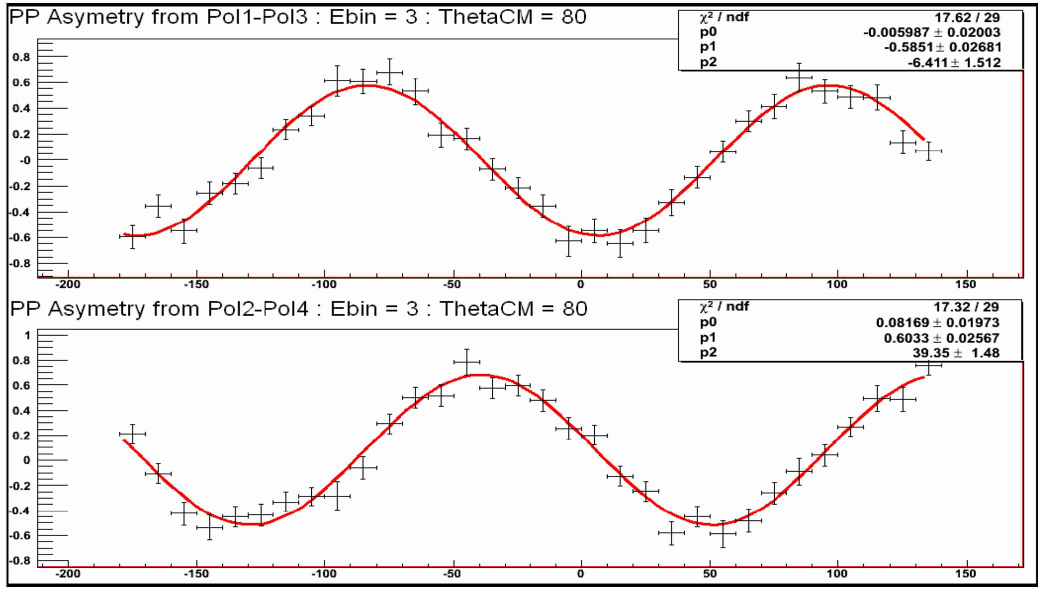
Pion Efficiency



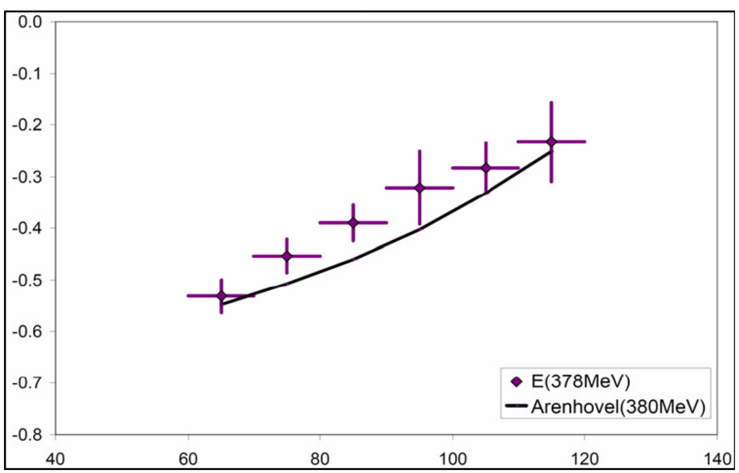
Missing Mass Resolution

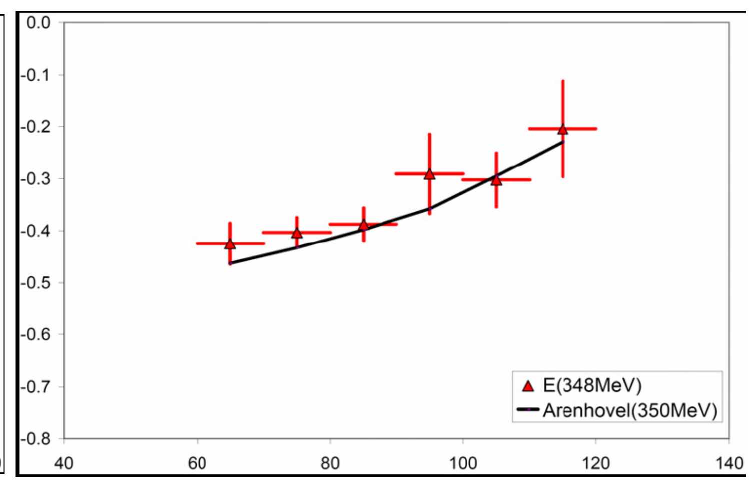


Beam Asymmetry for Pions



Σ, Beam Asymmetry



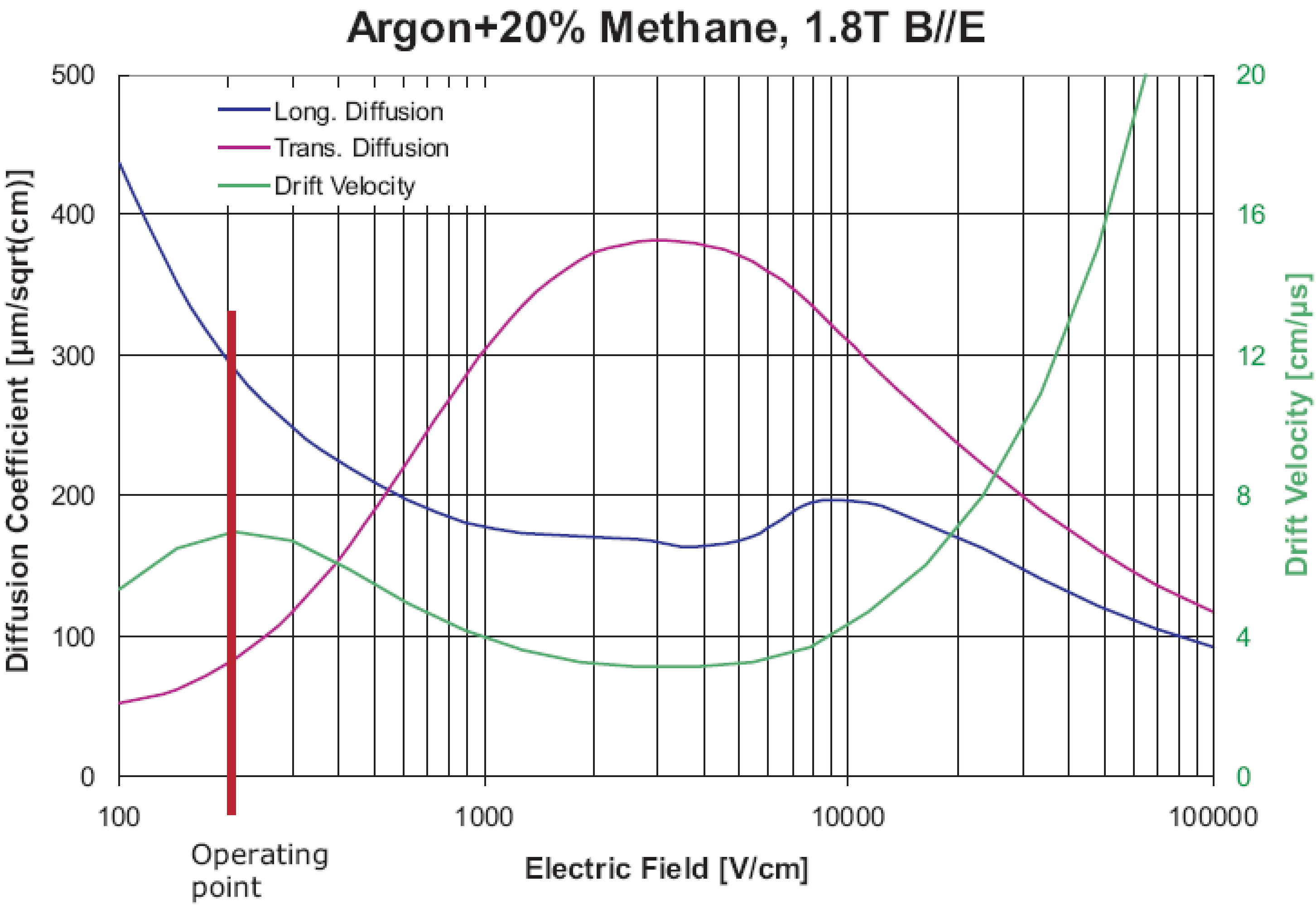


θ_{LAB} θ_{LAB}

The TPC Works Well.
Physics Results are Near!

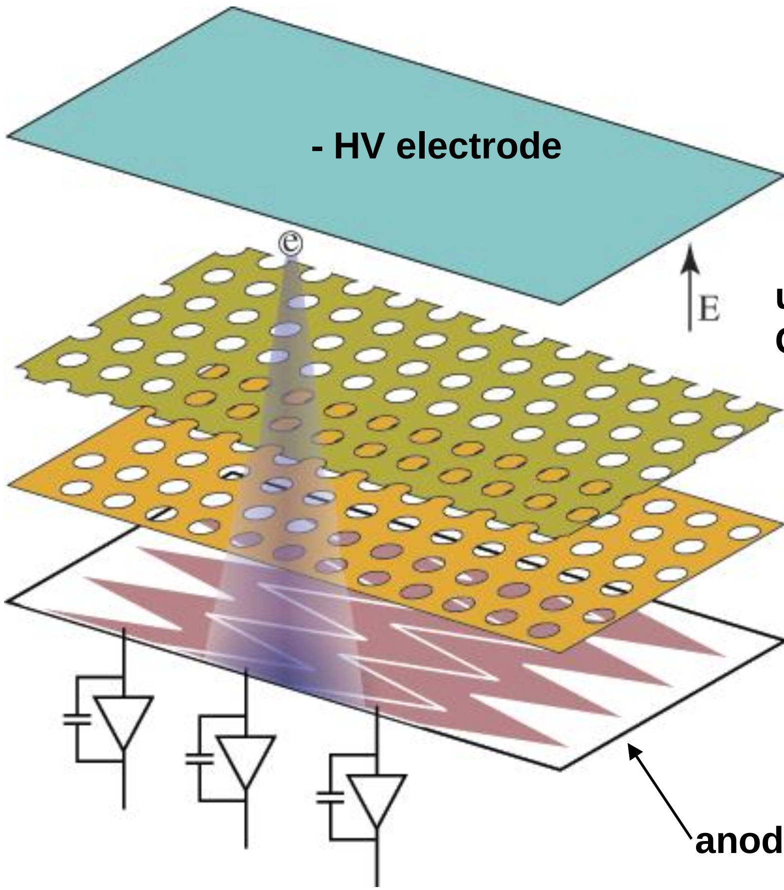
The End

Additional Slides

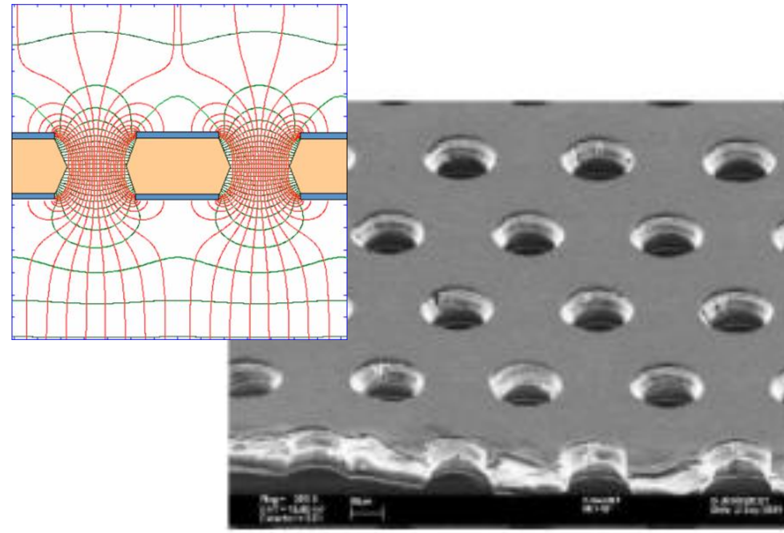


Argon+20% Methane, 1.8T B//E
Long. Diffusion
Trans. Diffusion
Drift Velocity
Diffusion Coefficient [µm/sqrt(cm)]
Drift Velocity [cm/µs]
Electric Field [V/cm]
Operating point
0
100
200
300
400
500
4
8
12
16
20
100
1000
10000
100000

Interpolating Zigzag Pad Readout with Double GEM for Charge Amplification

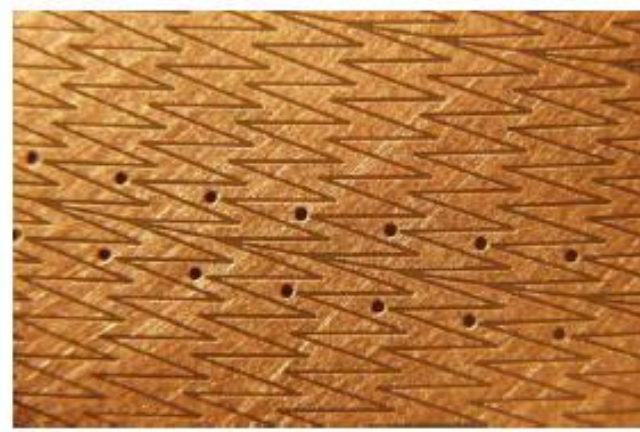


upper GEM



lower GEM

anode pad plane



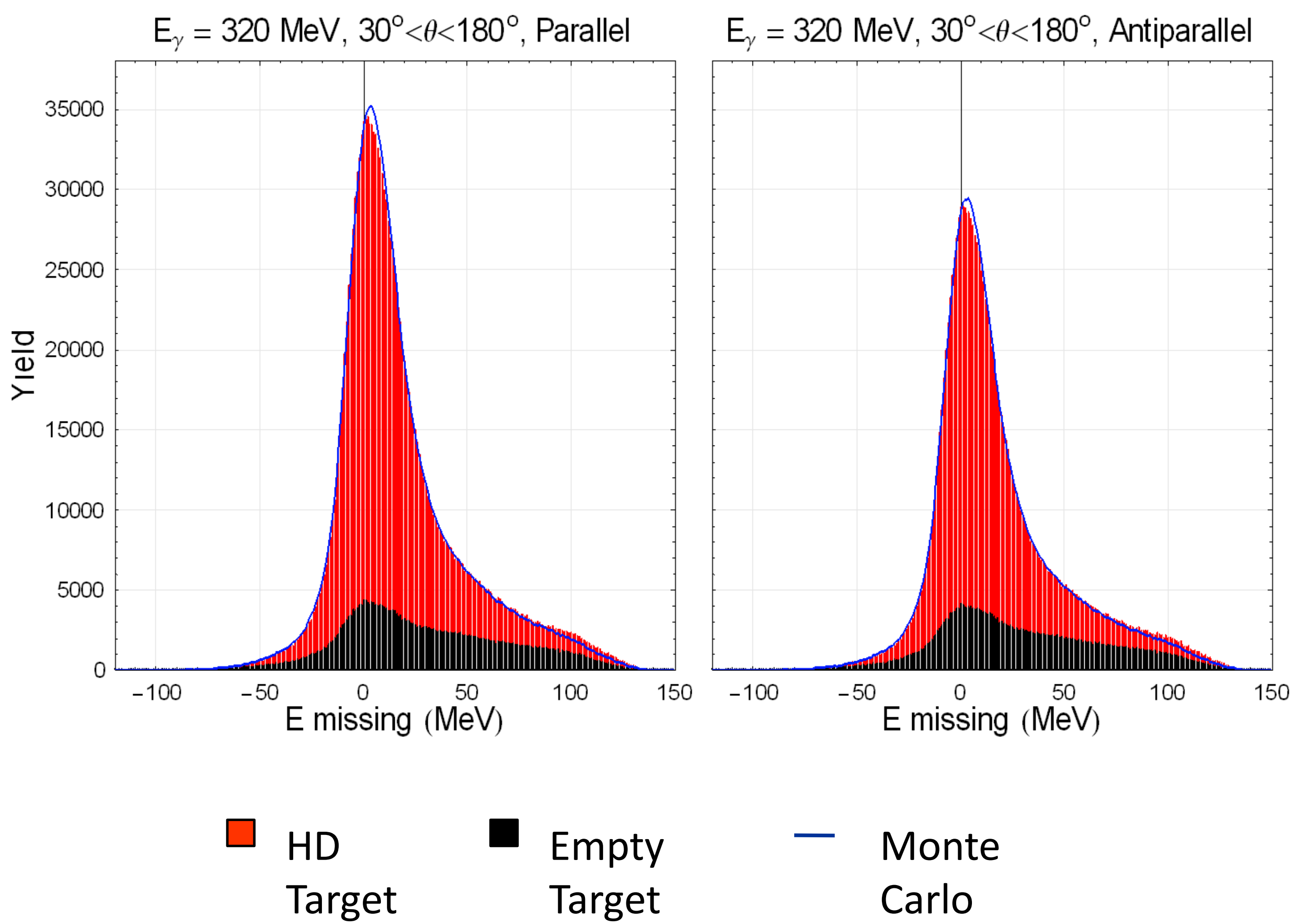
front-end electronics
7296 channels

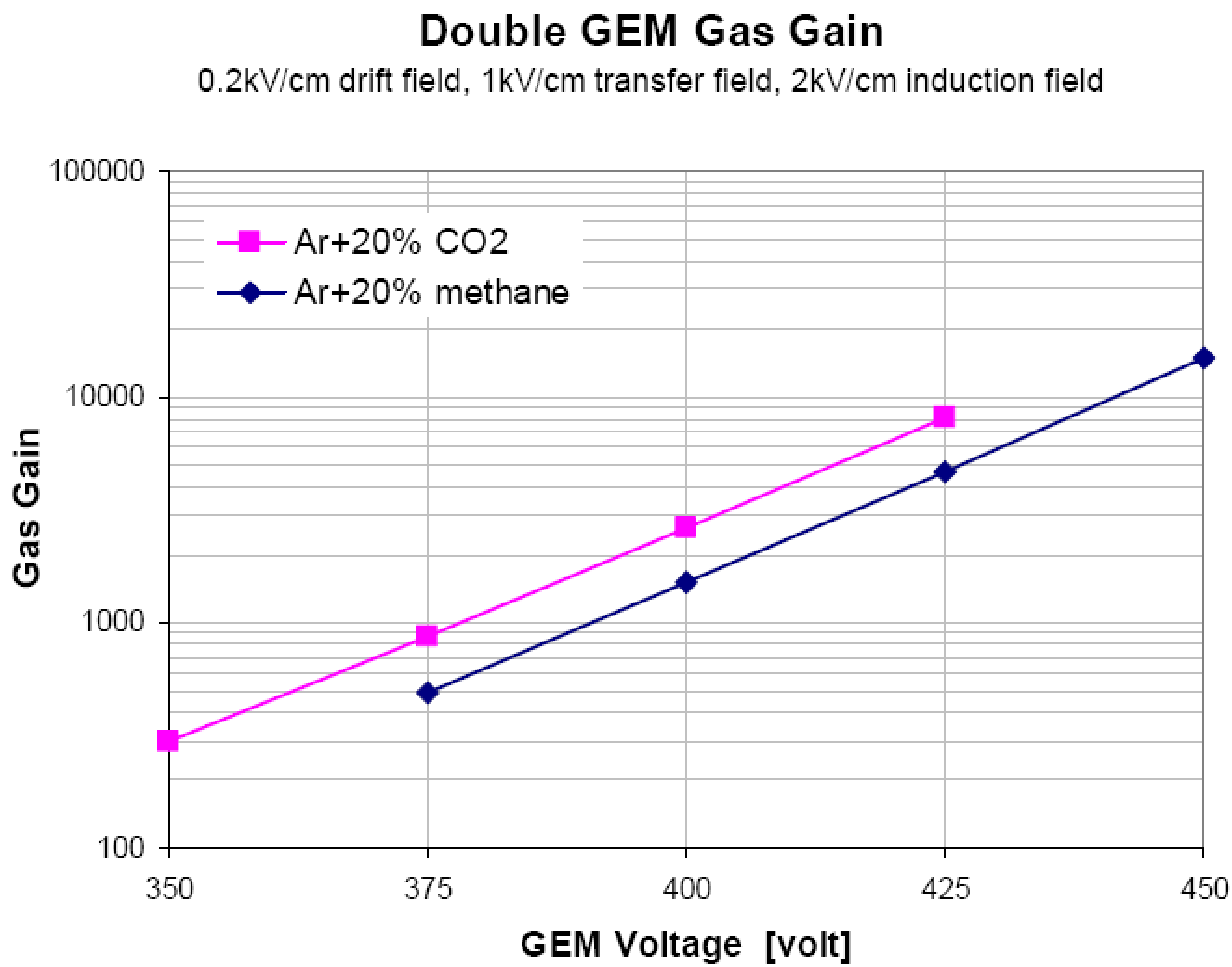
resolution is 140 μm rms for zero drift

Missing energy distributions for $\vec{\gamma} + \vec{H}\vec{D} \rightarrow \pi^0 + X$

Difference between 2-body kinematics and the measured π^0 energy

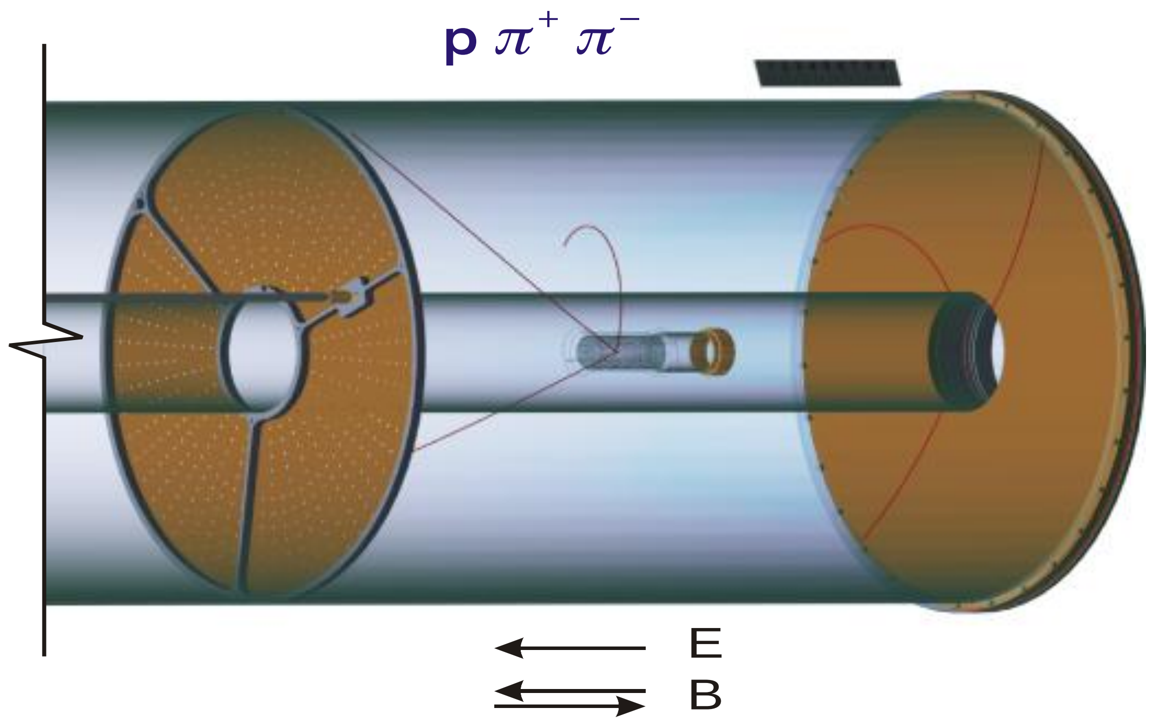
Most of target is HD
About 22% of π^0 come from Al cooling wires and Kel-F cell



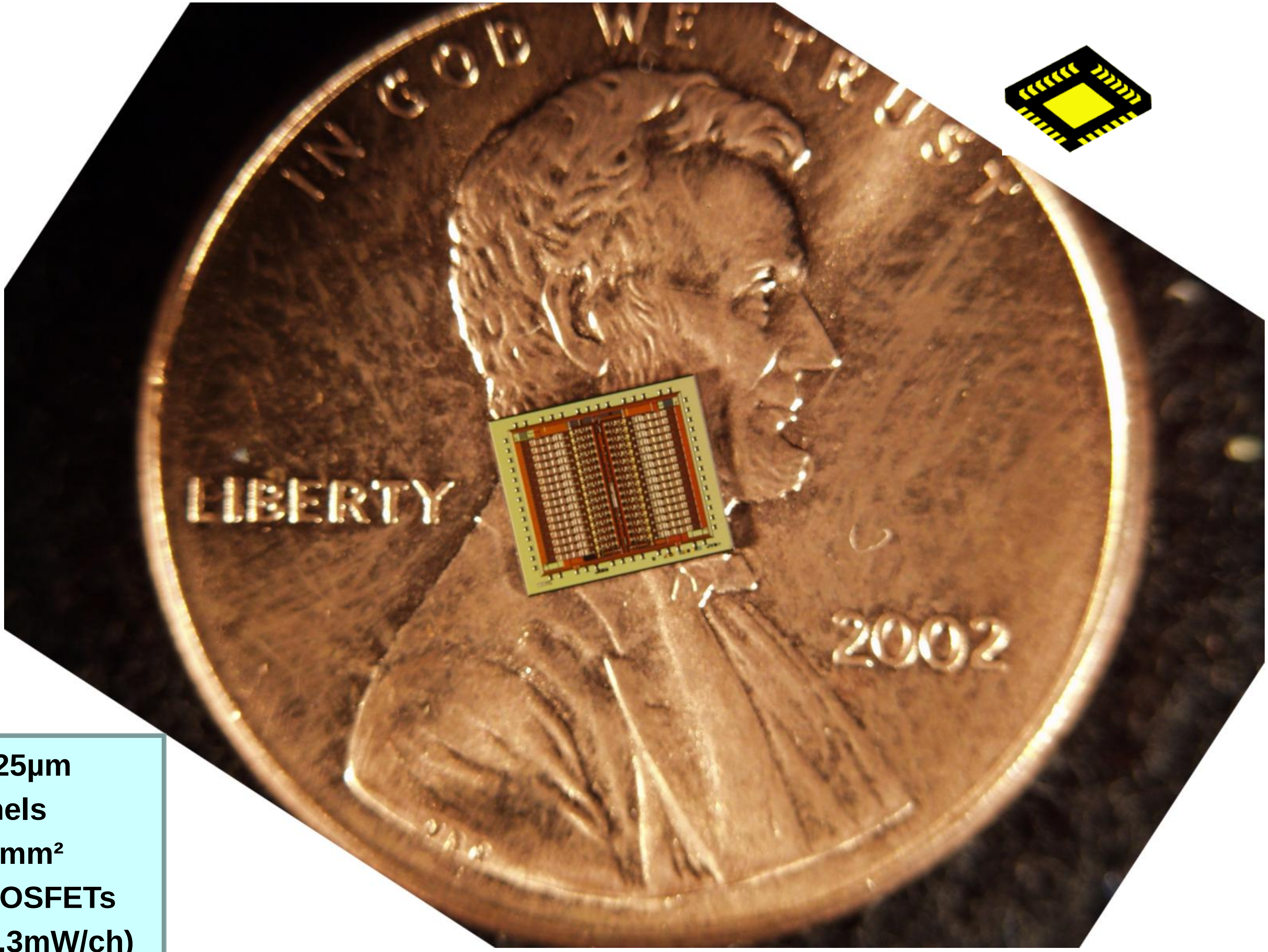


Double GEM Gas Gain
0.2kV/cm drift field, 1kV/cm transfer field, 2kV/cm induction field
100000
10000
1000
100
Gas Gain
Ar+20% CO2
Ar+20% methane
350
375
400
425
450
GEM Voltage [volt]

Track Projection in a TPC



Die Photo of ASIC for LEGS Time Projection Chamber

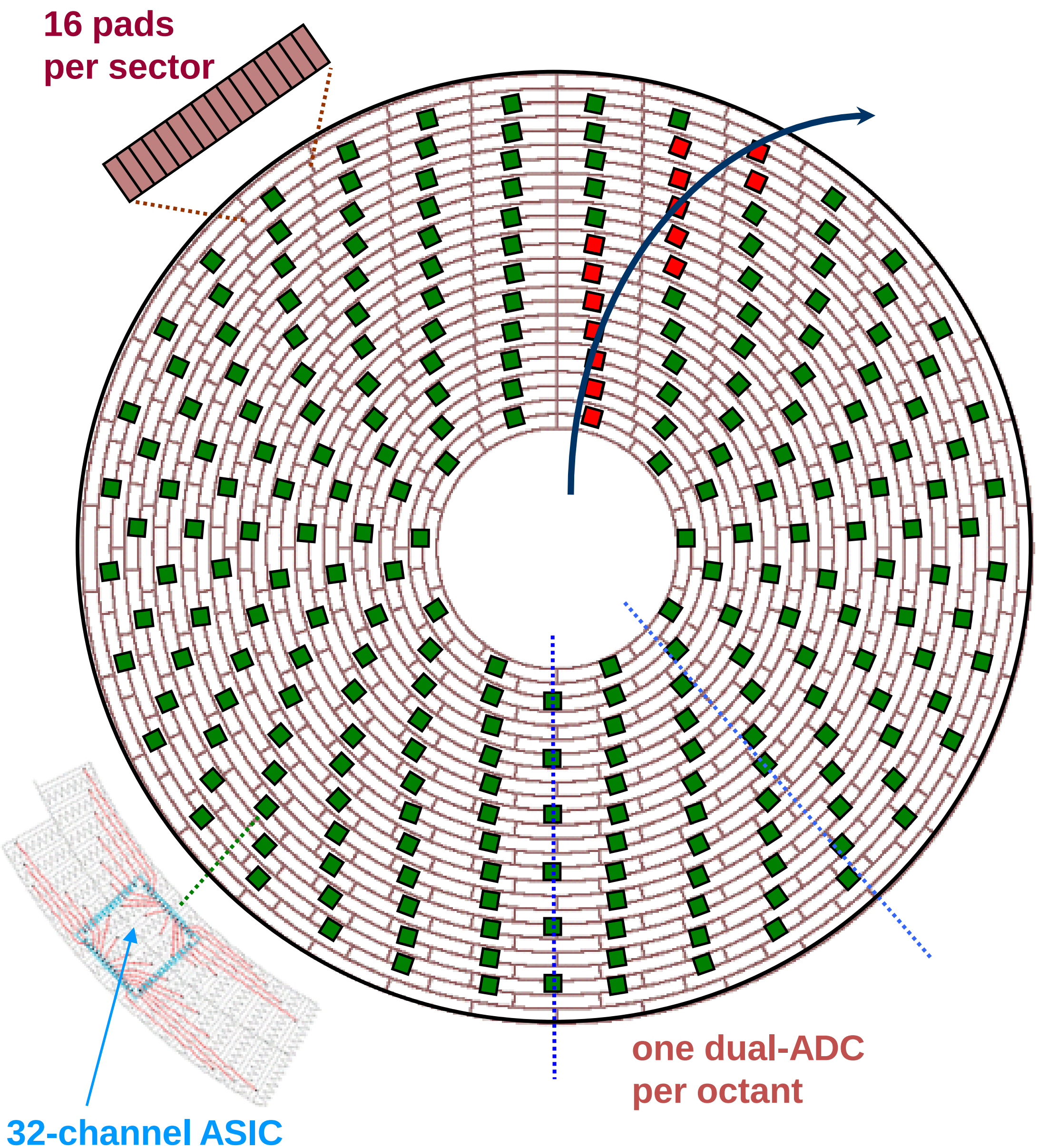


- TSMC 0.25µm
- 32 channels
- 3.1 x 3.6 mm²
- 47,000 MOSFETs
- 43mW (1.3mW/ch)
- QFN-56 package

Photo by Anand Kandasamy

G. De Geronimo, J. Fried, B. Yu (Instrumentation Division/BNL) – C. Thorn (LEGS/BNL)

Pad Plane with Front-End Electronics – Specifications



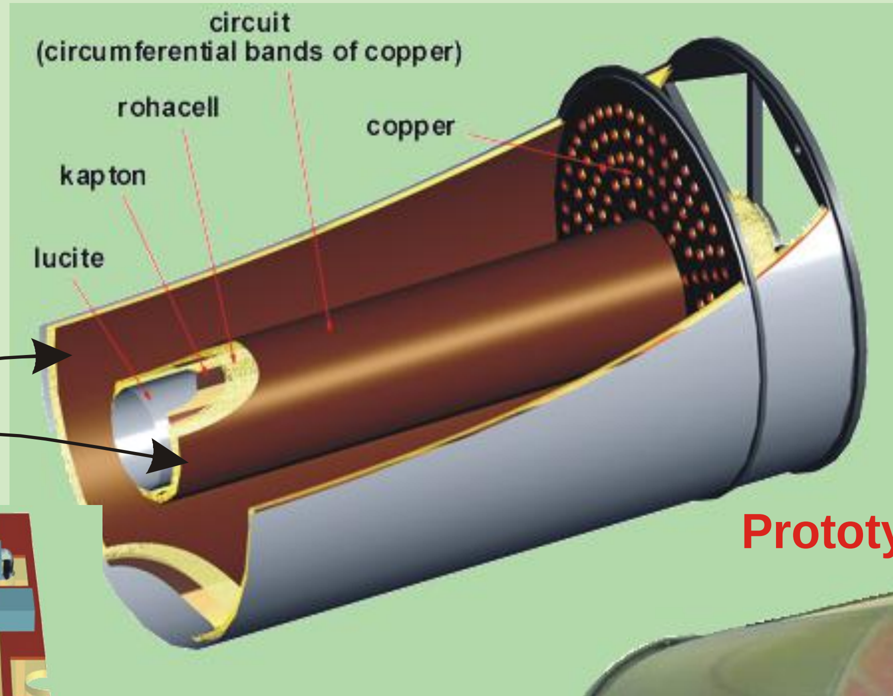
Tracking Measurement

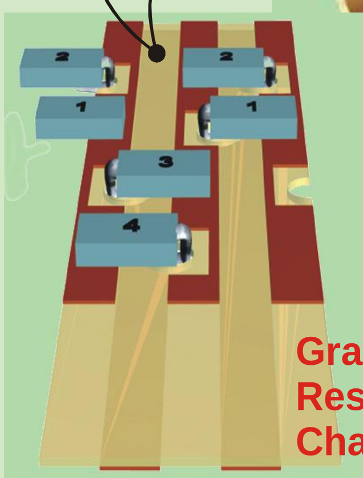
- Energy - triggered pad
- Energy - neighbor pads (centroid)
- Timing of triggered pad (z)

Specifications

- ENC < 500 e^- rms
- Timing < 20ns rms
- <u>Preamplifier</u>/shaper/BLH
- Adjustable gain ≈ 17-32 mV/fC
- <u>Peak-detector</u>
- Neighbor channel/chip enable
- Timing-detector (TAC)
- Channel masking
- Calibration
- On-chip buffers
- <u>Token/flag readout</u>

Drift Volume with HV Electrode and Gradient Rings



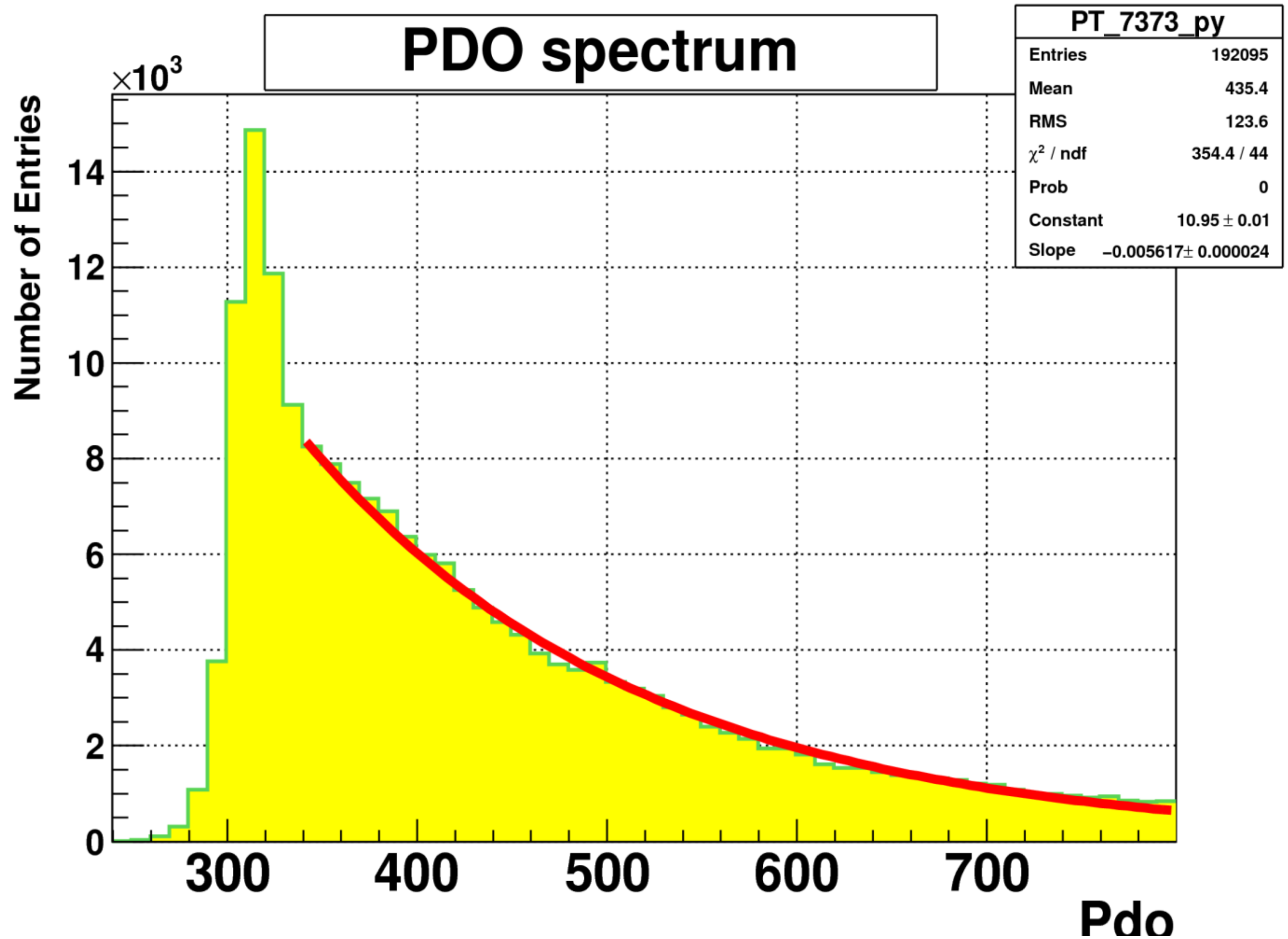


Gradient Rings &
Resistive Divider
Chain (2MΩ per resistor)

Prototype TPC Can

LEGS TPC Design Parameters

Inner active diameter	8.7 cm
Outer active diameter	35.7 cm
Active length	50 cm
Overall length	90 cm
Operating electric field (voltage)	200 V/cm (10 kV)
Maximum magnetic field	1.95 T
Track distortion ($\Delta\phi$) from B_r	<1 mm
Drift time	<7 μs
Filling gas	Ar + 20% CH_4
Gas multiplication	~1600 by double GEM
Peadout channels	7296
Δx, Δy resolution	<600 μm
Δz resolution	<1800 μm
Angular coverage	$20^o < \theta < 155^o$
Dead time per event	~400 μs
Average event size	200 words


PDO spectrum
PT_7373_py
Entries 192095
Mean 435.4
RMS 123.6
χ² / ndf 354.4 / 44
Prob 0
Constant 10.95 ± 0.01
Slope −0.005617± 0.000024
×10³
Number of Entries
0
2
4
6
8
10
12
14
300
400
500
600
700
Pdo